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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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CALCAREOUS ALGAE OF THE UPPER LEADVILLE LIMESTONE NEAR GLENWOOD SPRINGS, COLORADO

BY J. HARLAN JOHNSON

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ABSTRACT

Calcareous algae occur in considerable quantity in certain portions of the upper Leadville limestone near Glenwood Springs, Colorado. They include two species of *Solenopora*, two species of *Garwoodia*, four species of *Ortonella*, fragments of Dasycladaceae of the genus *Coelosporella*, one *Girvanella*, and at least four unnamed forms of Spongiostroma. None has previously been described from the United States. Three new species—*Solenopora glenwoodensis*, *Garwoodia media* and *Ortonella coloradoensis*—are described; others such as *Solenopora similis* Paul, *Garwoodia* aff. *Gregaria* (Nicholson), *Ortonella furcata* Garwood, *Ortonella* cf. *kershopensis* Garwood, and *Girvanella? nicholsoni* (Wethered) have been previously described from Great Britain. Remains of other organisms occurring with the algae are tabulated; a few are illustrated to throw light on the conditions of deposition of the limestone.

INTRODUCTION AND ACKNOWLEDGMENTS

Algal material occurs in appreciable quantities in the Leadville limestone of the Glenwood Springs region of Colorado. Although algal material has been reported

to be abundant in the Mississippian of England (Garwood, 1931a; 1931b; Wood, 1940–1943), Belgium (Gurich, 1906; Kaisin, 1926; 1927), and France (Derville, 1931), the author knows of only two references to finds in the American Mississippian, and those references only mention isolated occurrences (Fenton and Fenton, 1939; Ulke, 1938). Especially interesting is the fact that the algae in the Leadville limestone are quite similar to those found in the English Mississippian and represent the first record of these forms in the American Mississippian.

Locally, algal material is sufficiently abundant to form layers or streaks of algal or algal-foraminiferal limestone. In the course of the search for and study of the algae the writer noted the other fossils present. This information has been tabulated and presented to assist in showing the algal ecology as well as the origin of the limestone itself.

The study is based on material collected by the author in the course of field work during 1931, 1934, 1937, 1940, and 1941. Approximately 600 specimens of limestone and 250 thin sections were studied. Originally a much larger paper was planned to include descriptions of the organisms associated with the algae. However, war work interrupted the study. Now after several years' delay it seems wise to publish the completed portion in as much as further work on the material appears to be indefinitely postponed.

The writer wishes to thank the Colorado School of Mines for laboratory and library facilities and W. A. Waldschmidt and J. C. Haff who assisted in preparing the photomicrographs.

STRATIGRAPHY AND DISTRIBUTION

In the Glenwood Springs region the Leadville limestone includes two distinct members, an upper, massively bedded, "oölitic" limestone, and a lower member of well-bedded dolomitic limestones. The upper member is a prominent cliff maker (Pl. 1) and has an oölitic texture which, however, is often too minute to be recognized without a glass. The present paper deals only with material from this member.

The "oölitic" member has been observed in the area between Glenwood Springs, Aspen, Minturn, and north of Sweetwater Lake (Johnson, 1944). It attains its best development in the vicinity of Glenwood Springs and around the canyon of the Colorado River east of Glenwood (Bassett, 1939, p. 1860; Vanderwilt and Fuller, 1935, p. 455). In the Aspen district the "oölite" interfingers with dolomite and with other types of limestone. The same appears to be the case around Minturn (Fig. 1).

The detailed sections show some of the stratigraphic detail.

DETAILED SECTIONS

"Oölitic" member, upper Leadville limestone, on south side of river at mouth of canyon of Colorado River, Glenwood Springs, Colorado. Measured by J. H. Johnson, June 1940.

	Feet
Weber shale (Pennsylvanian)	
Unconformity	
Leadville limestone (Mississippian)	

FIGURE 1. MASSIVE LEADVILLE "OÖLITIC" MEMBER
Lime Creek valley at mouth of Little Lime Creek, Eagle County, Colorado.

FIGURE 2. LEADVILLE "OÖLITIC" MEMBER FORMS THE UPPER CLIFF.
Valley of No Name Creek near junction with Colorado River.

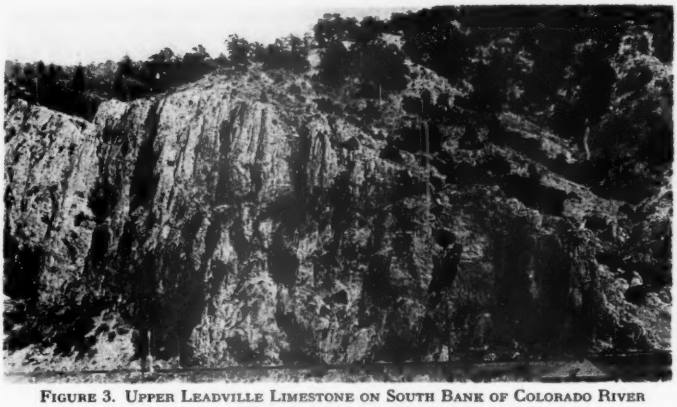

FIGURE 3. UPPER LEADVILLE LIMESTONE ON SOUTH BANK OF COLORADO RIVER
Glenwood Springs, Colorado.

OUTCROP OF UPPER LEADVILLE LIMESTONE

Upper layers—limestone, badly weathered and recrystallized. 34

Partly covered.

Light-gray limestone, fractures into rectilinear pieces. Badly crystallized. 4.5

Crinoidal limestone containing a few Foraminifera and a few fragments of Bryozoa and echinoid spines. Rock coarse-textured at top, becoming finer toward base because of finer grinding of the crinoidal debris. 14

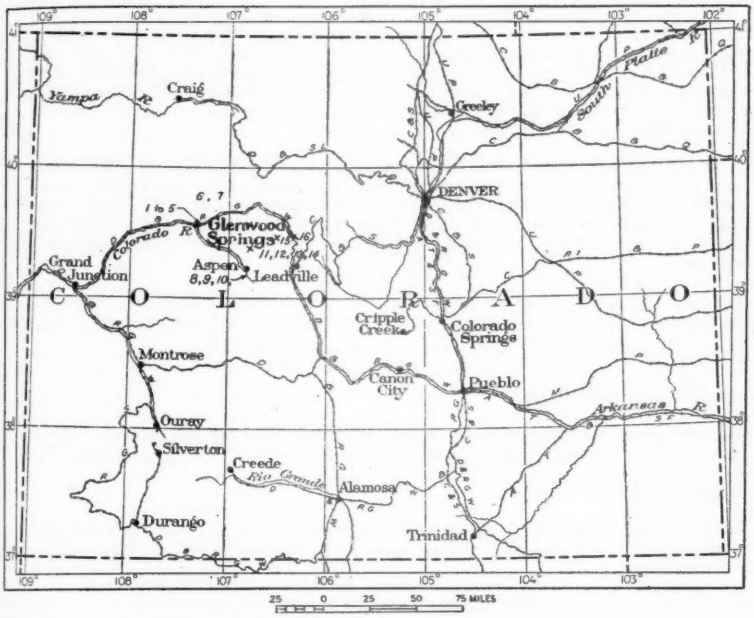

FIGURE 1.—*Map of Colorado showing location of Glenwood Springs*

Pseudo-oölite, massive, forms the gray ledge at mouth of canyon; shows practically no stratification. Composed of more or less rounded fragments of crinoids, echinoids, and Bryozoa with a few pieces of shell. Many of the fragments are covered with a dark coating of algal filaments. Similar filaments fill some of the organic fragments. Some rounded pellets of algal material occur. Foraminifera, especially *Endothyra*, occur sparingly throughout the rock. 41

Pseudo-oölite, forms lower massive ledge; similar to overlying bed but contains more Foraminifera and algal material. These both occur throughout the rock but are especially abundant in certain streaks and lenses. 37

About 8½ feet above base is a well-defined "algal zone" 4 to 6 inches thick. To the naked eye it appears as a fine-grained limestone with small, irregularly rounded pellets of a lighter color (Pl. 2, fig. 4). Microscopic examination shows this "algal zone" to be an algal-foraminiferal limestone enclosing only a very small amount of organic debris. The algal material includes colonies of *Mitcheldeania*, *Ortonella*, and *Solenopora*, a few very poorly preserved fragments of Dasycladacea, and an abundance of pellets and mats of poorly preserved filamentous types.

Below the algal zone the rock grades downward into a light-gray, nearly structureless limestone. 5

Dark, fine-grained limestone, slightly dolomitic, essentially an algal foraminiferal limestone. Foraminifera abundant, several genera represented.

The rest of the section consists of well-bedded, dolomitic limestones and dolomites.

Upper oölitic member Leadville limestone at the Garfield-Eagle County line, on north side Colorado River. (After Bassett.)

	Feet
"Limestone, black, oölitic, in one massive bed—Unfossiliferous except in uppermost portion where a few cup corals, branchiopods, and small cephalopods were found. The following brachiopods have been identified: *Schellwienella inflatus, Dictyoclaustus parviformis, D. semireticularis, Linoproductus ovatus, Ehipidomella burlingtonensis, Spirifer centronatus, Reticularia cooperensis, Seminula humilis.* The surface is pitted with sinkholes, which have been filled with rounded, weathered, and iron stained boulders and cobbles of this limestone. In some places the depressions are filled with Pennsylvanian shale." (Bassett 1939, p. 1960)	129

Microscopic examination of the rock shows it to be a pseudo-oölite similar to that at Glenwood Springs, containing an abundance of crinoidal fragments and Foraminifera (mainly *Endothyra*) with lesser amounts of bryozoan and shell fragments and a few echinoid spines. Some true oolites are present. Pellets of algal material are present as well as dark coatings of algal filaments around some of the organic fragments. A few streaks of ostracods were noted

Leadville and upper part of the Chaffee formations, just north of old Express Mine on Express Creek, a mile south of Ashcroft, about Sec. 32, T. 11 S., R. 84 W., Pitkin County, Colorado. Measured by J. H. Johnson and E. H. Stevens, June 30 and July 1, 1937.

	Feet
Weber shale (Pennsylvanian)	
Unconformity—Contact covered on the surface, but as exposed in a near-by pit it appears as a nearly horizontal surface. Upper layers of Leadville show weathering and solution effects.	
Leadville limestone (Mississippian)	
Limestone, pseudo-oölite. Blue gray on weathered surface. Dark gray when fresh. Massive beds, carries corals, crinoid stems, fragments of brachiopods, and abundant Foraminifera.	8
Limestone, pseudo-oölite with algal-foraminiferal streaks. Dark-gray, massive beds above, also fine-grained concentric masses and crusts of algal filaments around corals (Pl. 2, fig. 5). *Ortonella* abundant.	10
Limestone, pseudo-oölite. Gray, medium-bedded. Rock has a granular texture as a result of much organic debris. Crinoid stems, dark algal pellets and streamers, horn corals up to 3 inches long, a few conical gastropods, heads of *Syringopora* up to 8 inches in diameter	4
Limestone containing considerable fine organic debris. Slight bituminous odor on breaking	17
Dolomite, gray, weathering brown. Beds 4 inches to a foot thick.	14.5
The rest of the section consists of well-bedded, alternating limestones and dolomites with the dolomites becoming thicker toward the base.	

Meredith section of the upper part of the Leadville limestone. Old quarry about one-quarter mile south of Meredith in Sec. 14, T. 8 S., R. 8 W., Pitkin County, Colorado. Measured by J. H. Johnson and H. Mendenhall, July 28, 1937.

	Feet
Weber shale (Pennsylvanian)—outcrops on flats to north.	
Unconformity—contact covered by terrace gravels.	
Leadville formation (Mississippian)—a little of the top may have been covered.	

5 Limestone, pseudo-oölite. Dark gray with streaks of lighter, highly organic limestone. Beds massive. Gray, algal-foraminiferal limestone 8 feet below the top. All beds contain abundant fragments of crinoids, ostracods, some echinoid spines; Foraminifera plentiful. Many of the organic fragments are coated with algal filaments. A few large gastropods near base. 14

TABLE 1.—*Localities*

1—Glenwood Springs; mouth of canyon of Colorado River on S. side of the river along D. & R. G. railroad, Sec. 10, R. 89 W., T. 6 S.

2—Same as No. 1 except on N. side of river along Highway 40 S.

3—Quarry No. 1 about half a mile NW. of Glenwood Springs on north side Highway 40 S. (lowest quarry) about W. side Sec. 4, T. 6 S., R. 89 W.

4—Quarry No. 2, approximately same locality as No. 3, but higher up the hill.

5—Quarry No. 3, approximately same locality as No. 4, but about ¼ mile higher uphill.

6—Dotsero section of Bassett, on N. side Colorado River at county line of Eagle and Garfield counties, Sec. 11, T. 5 S., R. 87 W.

7—NW. side of Sweetwater Lake, Garfield County, approximately Sec. 8, T. 3 S., R. 87 W.

8—Cliff above Midnight Mine, Aspen district, Pitkin County.

9—Old Express Mine, on Express Creek, SE. of Ashcroft, Pitkin County.

10—Headwaters Little Express Creek about 3 miles SE. of Ashcroft, Pitkin County.

11—Old Meredith quarry, Sec. 14, T. 84 W., R. 8 S., Pitkin County.

12—Old Thomasville Quarry on N. side Frying Pan River at mouth of Lime Creek, Pitkin County, Sec. 18, T. 8 S., R. 83 W.

13—New Thomasville Quarry on S. side Frying Pan River, Pitkin County, Sec. 18, T. 8 S., R. 83 W.

14—Lime Creek just S. of mouth of Little Lime Creek, Eagle County, approximately NE. corner Sec. 33, T. 7 S., R. 83 W.

15—Along East Brush Creek about ¼ mile above Fulford Camp Ground, Eagle County.

16—Small quarry at S. end of Minturn, Eagle County, Sec. 26, T. 5 S., R. 81 W.

17—Along New Castle-Buford Road about ½ mile from U. S. Forest Service's Clark Cabin Camp Ground, Garfield County, probably T. 3 S., R. 91 W.

18—East Canyon Creek above Okanela Lodge, Garfield County, approximately Sec. 13, T. 5 S., R. 90 W.

19—W. side of Cement Creek at head of gulch just S. of ranger station.

20—About ½ mile NNE. of No. 19 along ridge W. of Cement Creek.

4 Limestone, pseudo-oölite, dark gray, massive. Similar to that above. Contains large horn corals, *Syringopora*, and large gastropods. Streaks and lenses of foraminiferal-algal limestone. *Endothyra* and small foraminifera abundant. Algal filaments of several sizes. 17.8

3 Band of breccia composed of fragments of limestone and dolomite in a dolomitic matrix on a slightly wavy bedding plane. (Conspicuous band about half way down face of quarry.) Material considerably recrystallized. 0.6

2 Limestone, pseudo-oölite similar to beds 4 and 5. Dark gray, massive, pronounced bedding plane at base. Echinoid spines abundant, numerous algal pellets. Many of the organic fragments are coated by algal filaments. 9.2

1 Limestone, pseudo-oölite, dark gray, massive, similar to bed above but contains some true ooliths, sponge spicules, and an abundance of algal material. 26.4

Base exposed in quarry. Lower beds occur farther up adjoining gulch.

The material studied came from localities listed in Table 1.

LITHOLOGY

Four general types of rock were observed: true oölites, pseudo-oölites, foraminiferal-algal limestone, and algal limestone. There are gradations among all four types.

True oölites are rare. The rock is composed of spherical masses of fine, radiating, needlelike crystals of calcium carbonate arranged in concentric layers (Pl. 3, fig. 4). Usually the spheres (oöliths) are small, less than 1 mm.; they may, however, range up to a maximum diameter of 0.8 centimeters. They are well developed at the very top of the formation along Cement Creek in Gunnison County. Oölitic streaks and lenses occur at a number of localities, and some oölitic material is present in about half the samples studied. Calcareous algae are frequently associated with the oölites, and in many cases algal filaments occur within the individual oöliths. In some cases layers of algal filaments were observed between the concentric layers of $CaCO_3$ (Pl. 3, fig. 4). The algae are not believed to be responsible for the oöliths, but rather their presence in the oöliths is accidental. Apparently conditions favorable to the development of one favor the other. However, many cases are known of deposits of one without the other, so there is no necessary relation.

Oölites are usually interpreted as chemical precipitates in shallow, probably warm waters in localities where there was active circulation (Twenhofel, 1939, p. 573–577; Hatch, Rastall and Black, 1938, p. 175–178). However they may represent biochemical work of colonies of lime-secreting bacteria developing in or upon an organic mass in tranquil water. The associated organisms and physical characteristics of the rock appear to favor the first picture around Glenwood Springs.

Pseudo-oölites are composed of small, rounded, organic fragments which superficially look like fine-textured oölites. In thin sections the pellets are seen to represent worn fragments of crinoid stems, echinoid spines, Bryozoa, and shell fragments mixed with ostracods and foraminifera in a clear groundmass of crystalline calcite (Pl. 5, figs. 1, 2, 3, 5). The material may be coated by fine algal filaments and contain small algal pellets.

Remains of the following organisms were recognized in thin sections (given approximately in order of abundance): crinoid stems and plates, dark algal pellets, Foraminifera, echinoid spines, Bryozoa, ostracods, shell fragments. Plates of holothurians, fish teeth, and sponge spicules are rare. Oölites may occur with the organic debris. The particles may be coated with fine algal filaments (Pl. 2, fig. 5, Pl. 3, figs. 5, 6). This rock was the most common and widespread of the four types. It was present at all the localities studied and usually formed most of the deposit.

Foraminiferal-algal limestone is composed almost entirely of dark, algal material and Foraminifera (Pl. 2, figs. 1, 3). The foraminifera include *Endothyra* and a number of small types. Many of the larger are filled with fine algal filaments. Some of the tests are perforated by the algae.

The algal material forms rounded pellets and irregular, feltlike masses. A number of types of algae are present having filaments ranging from fine to very coarse (Pl. 4). Some of the slides suggest a mat of algal filaments with the Foraminifera entangled among them.

Algal limestones are composed predominantly of algal remains. They may consist of dark, algal pellets in a clear calcite groundmass (Pl. 3, fig. 5; Pl. 4, fig. 4; Pl. 5, fig. 1), or the groundmass of the rock consists of a feltlike mat of algal filaments enclosing small, scattered fragments of organic debris (Pl. 2, fig. 4). The algae are of the same types as found in the algal-foraminiferal limestones, and the two rock types grade into each other.

TABLE 2.—*Distribution of organisms in slides*

Number of slides studied	241
Algae	198
Foraminifera	127
Crinoidal fragments	107
Echinoid spines	84
Echinoid plate, fish tooth	1
Bryozoan fragments	99
Gastropods	8
Mollusk fragments	15
Ostracods	74
Corals	3
Brachiopods	12
Shell fragments (undeter.)	36
Sponge spicules	3

Large deposits of pure algal limestone are rare in the Leadville, although small streaks, patches, and bands were noted at several localities. They grade into algal-foraminiferal limestones which are more common and widespread.

FOSSILS IN THE LIMESTONE

The organisms recognized in the limestone include calcareous algae, Foraminifera, crinoids, echinoids, brachiopods, mollusks, and ostracods. Table 2 shows the relative distribution.

In terms of bulk of material contributed to the limestone, the order of relative abundance is approximately: crinoidal debris, Foraminifera, algae, Bryozoa, shell fragments (brachiopod and mollusk), echinoids. The other organisms contribute very little.

The high relative abundance of algae both in the number of slides and in bulk is probably not characteristic of the entire deposit as the specimens were collected to obtain algal material, not to give representative samples of the upper Leadville formation. Only material which contained or possibly contained algal material was collected.

INVERTEBRATE ANIMALS

Invertebrate remains, usually fragmentary, were recorded whenever observed and recognized but were not studied, and no attempt was made to identify them beyond phylum or class.

FORAMINIFERA: These are present in most slides studied. The genus *Endothyra*, largest and most abundant of the forms observed, appears to be represented by a

number of species mostly as yet undescribed. A number of genera of smaller Foraminifera were also present.

SPONGES: Sponge spicules are rare. They were definitely recognized in only three slides. Fragments that may have been such spicules were noted in a few others. They are small, smooth, and of transparent silica.

CORALS: These were observed in only three slides. One is a fragment of a small horn coral. The other two are cross sections of a medium-sized species of *Syringopora*. They are in material from Lime Creek and Express Creek.

ECHINODERMS: This phylum is abundantly represented by crinoidal debris and echinoid spines. The crinoidal debris consists mainly of stem fragments more or less badly broken and abraded (Pl. 5, figs. 1, 2, 6). A few fragments of calyx plates were recognized. Crinoidal fragments are the most abundant and bulky of the organic constituents of the limestone. Echinoid spines are abundant. They are numerous, few in kind, small, mostly smooth, and are easily recognized by their distinctive structure in cross section (Pl. 5, figs. 4, 6).

BRYOZOA: Fragments and shreds of Bryozoa are abundant and varied (Pl. 3, fig. 6; Pl. 5, figs. 1, 2). Usually they are small and worn (less than 1 mm. in greatest dimension), although some pieces of as much as 4.5 mm. were observed.

BRACHIOPODA: Shell fragments were observed in a number of slides. Often they are too small and abraded to permit satisfactory classification, but a few of the larger fragments represent brachiopods, particularly productids and Spirifers.

MOLLUSKS: A few shell fragments were recognized as belonging to mollusks. Small gastropods were noted in a few slides (Pl. 5, fig. 3), and embryonic gastropods and cephalopods in several others.

CRUSTACEANS: Ostracodes are present in many of the slides but in most cases are fragmentary and are represented by only a few individuals or a stray shell. At only one locality were they abundant (Pl. 5, fig. 5). They appear to represent smooth or poorly ornamented forms of two distinct sizes.

CLASSIFICATION OF ALGAE

The algae found in the Leadville limestone are classified on the basis of: microstructure when present, size and shape of colonies, and growth habits. In the description the more complex forms are considered first, then progressively simpler ones. (See table on p. 837.)

SYSTEMATIC DESCRIPTION

CLASS RHODOPHYCEAE

FAMILY CORALLINA

SUBFAMILY SOLENOPORACEAE

Genus *Solenopora* Dybowsky, 1877

Attempts have been made in recent years to break this general type into several genera, but the authors are not in agreement and have not been successful in applying their classifications to Paleozoic forms. Following the examples of Garwood (1931b, p. xcv) and Pia the writer continues to use the term *Solenopora* in a broad sense.

Key to algal groups described

Rhodophyta (Red algae)	*Solenopora*	Rows of cells so closely spaced as to assume polygonal cross sections. Cross partitions are present, though frequently very thin.
Chlorophyta (Green algae)	Dasycladaceae	A central stalk, tubular or bulb-shaped, surrounded by simple or brushlike clusters of leaves or leaf bases showing as knobs or brushlike protuberances.
	Codiaceae *Garwoodia* *Ortonella* *Hedstromia* *Bevocastra* *Polymorphocodium* Codiaceae? *Gymnocodium*	Small tubes loosely arranged. Tubes round in cross-section and branching.
Chlorophyta? Possibly Cyanophyta	Porostromata *Girvanella* Numerous unnamed types	Small tubelike filaments so loosely arranged that they are not flattened. No cross partitions visible.
Cyanophyta (Blue-green algae)	Spongiostroma	Shows little or no cellular structure. The calcium carbonate is deposited as crusts on the outside of the filaments or between the tissues, not in the cell walls. Sometimes filament walls indicated by carbon films, more often as molds or casts. Include many encrusting and perforating types.

Several occurrences of *Solenopora* were noted at Locality 1. All were pieces of colonies somewhat frayed and worn little can be said as to the original size and shape of the colonies. Two species were recognized.

Solenopora similis Paul

(Plate 3, figure 1)

1938. *Solenopora similis*, Paul, Decheniana, Bd. 97A, p. 19 (15), Pl. 3, figs. 2–3.

Description: Occurs as fragmentary masses ranging in size from 0.6 to 1.6 cm. The largest observed measured 0.7 by 1.6 cm. In longitudinal section the structure appears as a series of closely packed, subparallel tubes radially arranged. The walls are straight and thin (0.003 cm.). Cross partitions are well developed and closely spaced. The tubes average 0.03 cm. across and show only slight variations from this average. The partitions are spaced 20 to 30 μ apart, averaging 24 μ (0.024 mm.). Thus the average cell size is 24 μ long and 30 μ wide.

Remarks: The size and shape of cells (26 μ long and 21 to 37 μ wide) agree closely with Paul's description although the average length is slightly less. The arrangement of the cells appears to be the same.

Occurrence: Glenwood Springs, Colorado, on south bank of Colorado River at the mouth of the canyon.

Solenopora glenwoodensis n. sp.

(Plate 3, figure 3)

Holotype: Slide No. 808 from specimen JA 1897d, Johnson Collection, Colorado School of Mines.

DESCRIPTION: Occurs as fragmentary masses about 0.5 cm. in size. In longitudinal section the structure appears as a series of closely packed, subparallel tubes. These have a radial arrangement. They are somewhat sinuous, weaving up and down from the plane of the section. The walls are slightly wavy and thin (about 0.005 mm.). The tubes have a width of 42 to 46 μ and observed lengths of 77 to 92 μ. In cross section the tubes are round to subpolygonal. Average diameter of tubes 42 μ. Partitions poorly developed, spaced 34 to 50 μ apart, average 45.

TABLE 3.—*Distribution of algae studied in slides*

Number of slides examined	198
Solenopora	3
Garwoodia	26
Ortonella	39
Very coarse filaments (large at × 15)	13
Coarse filaments (plainly visible at × 15)	57
Medium coarse filaments (just visible at × 15)	20
Medium filaments (suggested at × 15, plain at × 50)	140
Fine filaments (suggested at × 50, visible at × 125)	181
Algal coatings organic fragments	73
Algae perforating organic fragments	27
Algae filling Foraminifera or ostracods	82
Gymnocodium	2
Dasycladaceae fragments	17
Oöliths present	52

REMARKS: The tubes were much more twisted than those of *S. similis*, which are very regular. They thus appear very irregular in thin section, so the long dimensions recorded are probably considerably short of the reality.

The described species nearest *S. glenwoodensis* is *S. garwoodi* Hinde, *S. garwoodi* has relatively straight tubes and well-developed partitions, whereas *S. glenwoodensis* has sinuous tubes and poorly developed partitions. *S. garwoodi* has cells which show considerable variations in size, but on the average they are slightly narrower and considerably shorter than *S. glenwoodensis*.

OCCURRENCE: Glenwood Springs, Colorado, along south bank of Colorado River at mouth of canyon.

CLASS CHLOROPHYTA

SUBCLASS CHLOROPHYCEAE

ORDER SIPHONOCLADIALES

FAMILY DASYCLADACEAE

Genus ***Coelosporella*** Wood, 1940

GENERAL: A number of slides show poorly preserved, badly macerated fragments of objects which suggest Dasycladaceae. Some may really be echinoid spines. A few closely resemble *Coelosporella* recently described from the Mississippian limestone of north Wales (Wood, 1940, p. 16), but they are somewhat smaller. This could represent a difference in species. However, the material is too fragmentary to justify erecting a new species, so the occurrence is mentioned in the hope it will stimulate a search for better material.

ORDER SIPHONALES

FAMILY CODIACEAE

Genus ***Garwoodia*** Wood, 1941

GENERAL: Wood (1941a) restudied the available type material of *Mitcheldeania* and found it to represent a mixture of at least three genera of algae. He classed these as an unusually coarse

Girvanella, *Bevocastria*, and *Ortonella*. The form with the peculiar, double right-angled branching (Pl. 3, fig. 2), which several generations of paleontologists have considered the peculiar and easily recognizable characteristic of *Mitcheldeania*, he renamed *Garwoodia*, genotype *Mitcheldeania gregaria* Nicholson. His description is as follows:

"Moulds of algal threads occurring in nodules and having a marked radial direction. The threads are practically straight for long distances, so that a very characteristic appearance is seen in section. Branching occurred rather frequently. The new thread was given off almost at right angles from the parent, and then bent around rapidly to grow parallel with the other threads. All threads close together, subparallel, and sub-equal in diameter" (Wood, 1941a, p. 221–222).

Garwoodia aff. *gregaria* (Nicholson)

(Plate 3, figure 2)

DESCRIPTION: Characterized by a tube diameter ranging from 0.05 to 0.072 mm. Several colonies and fragments of colonies were found in the Leadville material which had tube diameters between 0.048 and 0.06 mm., so are considered close to the species.

OCCURRENCE: Glenwood Springs, Colorado, at mouth of canyon on south side of Colorado River, and on Lime Creek at mouth of Little Lime Creek.

Garwoodia media n. sp.

(Plate 4, figures 2, 3)

HOLOTYPE: Slide No. 574 from specimen JA 1892, Johnson Collection, Colorado School of Mines

DESCRIPTION: Tubes ranging in diameter from 0.028 to 0.034 mm., averaging about 0.033 mm. Distance between threads where the calcite dust suggests a development of walls 13 to 15 μ.

REMARKS: This species is shown on 12 slides. All the specimens are fragmentary and represent only portions of colonies. The larger specimens show rather long, straight tube lengths between branches. In size this is similar to one mentioned, but not named, by Paul (1939, p. 14).

OCCURRENCE: Glenwood Springs, on south side Colorado River at mouth of canyon.

Genus *Ortonella* Garwood, 1913

Ortonella furcata Garwood

(Plate 4, figure 6)

1914. *Ortonella furcata*, GARWOOD, Geol. Mag., vol. 1, p. 265, Pl. 20, fig. 1–4.
1916. ———, GARWOOD, Geol. Assoc., Pr., vol. 27, p. 9, 24, Pl. 18, fig. 3.
1927. ———, PIA IN HIMER, Handbuch der Palaobotänik, vol. 1, Fig. 25.
1931. ———, GARWOOD, Geol. Soc. London, Quart. Jour., vol. 87, p. 130–132, 135–136, Pl. 14, fig 1.
1937. ———, PIA, Deuxième Congrès des études de stratig. Carbonifère, C.R., p. 790–791.

DESCRIPTION: Algal threads having diameters of 0.03 to 0.04 mm., branching at angles of about 40°. Form compact, oval to spherical colonies of small size.

REMARKS: A number of specimens of this form were observed. It represents the coarsest species of *Ortonella* described to date.

OCCURRENCE: Localities 1, 3, 6, 7, 9, and 14.

Ortonella cf. *kershopensis* Garwood

(Plate 4, figure 4)

1931. *Ortonella kershopensis*, GARWOOD, Geol. Soc. London, Quart. Jour., vol. 87, p. 111, 139, Pl. 13, fig. 3.
1937. ———, PIA, Deuxième Congrès des études de stratig. Carbonifère, C.R., p. 791–792.

DESCRIPTION: Garwood's species has a diameter of algal threads ranging from 0.01 to 0.0125 mm. and branching at angles of around 40°. In the Leadville limestones were numerous examples of a

similar organism having extremely fine threads of diameters from 0.011 to 0.0132 mm. and branching at angles of 40°–45°. They so closely approximate *O. kershopensis* as to be considered under that name.

REMARKS: This species is abundant and widespread in the Leadville. Usually the colonies formed small, spherical or irregularly rounded pellets.

OCCURRENCE: Present at all the localities studied.

Ortonella sp.?

DESCRIPTION: A typical *Ortonella* with thread diameters ranging from 0.019 to 0.022 mm. Branching at angles of 35°–40°.

REMARKS: This form was abundant at Glenwood Springs but mostly as frayed fragments of colonies. Unfortunately none of the slides showed specimens which would make distinctive photographs. In view of this and of the fragmentary condition of the specimens it does not seem advisable to give it a specific name.

OCCURRENCE: Glenwood Springs, Colorado, on south side of Colorado River at the mouth of the canyon.

Ortonella coloradoensis n. sp.

(Plate 2, figure 2)

HOLOTYPE: Slide No. 449 from specimen JA 1832, Johnson Collection, Colorado School of Mines.

DESCRIPTION: A typical *Ortonella* with thread diameters ranging from 0.024 to 0.0272 mm. Branching at angles closely approximating 45°. Plant forms small tufts, rarely small nodular masses.

REMARKS: Several specimens of this species were observed growing on crinoid fragments. This species closely resembles *O. furcata* garwood except for a smaller tube diameter (0.24–0.27 mm. versus 0.40–0.33 mm.) and a slightly wider angle of branching.

OCCURRENCE: Glenwood Springs, Colorado, on south side of Colorado River at the mouth of the canyon.

CLASS CYANOPHYTA (POSSIBLY CHLOROPHYTA)

FAMILY POROSTROMA

Genus *Girvanella* Nicholson and Etheridge, 1880

Girvanella? nicholsoni (Wethered)

(Plate 4, figure 1)

DESCRIPTION: Moulds of coarse, somewhat twisted tubes having a concentric arrangement. They branch at rare intervals. Tube diameter 0.055 to 0.075 mm. Associated with colonies of *Garwoodia*, surrounding and growing in the colony.

REMARKS: The Leadville specimens fit Wood's (1941a, p. 219) description exactly so are listed as the same although the author thinks the use of the term *Girvanella* unfortunate as he considers the genus *Girvanella* to represent minute, highly twisted, unbranching tubes or threads with well-defined wall structure. Specimens of true *Girvanella* were not noted in the Leadville.

OCCURRENCE: Glenwood Springs and Lime Creek—Localities 1 and 14.

CLASS CYANOPHYTA

FAMILY SPONGIOSTROMA

(Plate 4, figure 5; Plate 3, figures 4, 5)

Most of the algae found in the Leadville limestone belong in this group. The organisms show no cellular structure and are indicated by carbon films, calcareous casts of filaments, calcareous

coatings accentuated by carbonaceous films, and calcareous coatings and casts of filaments and of layers of filaments. They have been classified on the basis of size of filaments and shape of colonies. Admittedly classification into "form genera" on the shape of the colony is very artificial, and the shape may represent largely a response to environment (Pia, 1928). However, studies of pre-Cambrian and Paleozoic algae of this type have shown that many of the form genera are surprisingly uniform over wide areas during certain portions of geologic time (Fenton and Fenton, 1937; 1938; 1939; Johnson, 1940, p. 579–590).

These form genera may represent true biologic genera or several biologic species or even several genera which lived in a constant close association. The form genera and species seem to have been sufficiently persistent to be recognized, and they developed colonies sufficiently different to be separated easily on megascopic characteristics when entire colonies are available. Microscopic examination shows constant differences in thickness and character of growth laminae and of size of filaments. These facts seem to make the classification more valid.

All the Leadville forms make small colonies. Usually they are less than a centimeter in diameter, although occasionally some are two or three times that size. Many are submicroscopic.

In the smaller colonies and forming a feltlike groundmass in much of the limestone are casts of extremely fine algal threads or filaments. These are preserved as moulds in very fine particles of calcium carbonate, the "algal dust" of Wood (1941b). They are recognizable only at high magnification, being less than 0.005 mm. in size. They are the most abundant and widespread of all the algal types recognized from the Leadville.

Other types occur as separate colonies and intermixed with each other and the very fine threads. Whereas there is a great variety of sizes, over 90 per cent of the filaments measured fall into four size ranges.

	Mm
Coarse	0.048–0.056
Medium coarse	0.037–0.042
Medium	0.022–0.028
Fine	0.010–0.017

Nearly all the filaments branch.

Variations in size of the threads are the only distinctive features noted; consequently there is no justification for proposing names for them.

Perforating Algae

(Plate 4, figures 5; Plate 5, figures 2, 3, 4)

Some of the algae were perforating types, penetrating the edges of the crinoidal debris and shell and bryozoan fragments. Cavities in Foraminifera, ostracods, small gastropods, and bryozoan fragments are filled with fine algal material in most of the slides studied.

Algal Coatings

(Plate 3, figures 5, 6; Plate 4, figure 5; Plate 5; figures 1, 2, 6)

Much of the pseudo-oölite consists of more or less rounded fragments of organic debris coated with fine algal filaments. These show as a dark-gray to black envelope around the bit of shell or piece of crinoidal or bryozoan shred. The algal material constituted from 10 to as much as 60 per cent of the volume.

Algae and Oöliths

In a number of the slides studied algae and ooliths occurred together or side by side. Figure 4 of Plate 3 shows an interesting intergrowth. Black bands of fine algal filaments are enclosed between layers of the clear needles of crystalline calcite characteristic of the oöliths. Presumably the needles represent chemical precipitates, although bacteria may have played a part in their formation.

CONDITIONS OF LIMESTONE DEPOSITION

ECOLOGY

Available Ecology information suggests the pseudo-oölites were deposited in temperate, shallow to moderately shallow marine waters. The arm of the sea was probably largely surrounded by low-lying lands which supplied little sediment but whose streams brought in considerable calcium salts in solution.

All waters probably supported a luxuriant growth of algae which furnished the basic food for an abundance of sessile animals such as crinoids, Bryozoa, and locally corals. Echinoids were abundant in some localities, and gastropods in some. A few brachiopods were present. Foraminifera were plentiful in the waters; locally they were extremely abundant.

Among the numerous algae present were some lime-precipitating forms and a few lime-secreting types.

CONCLUSIONS

Algae of many types were abundant in the Leadville sea. Among them were numerous lime-precipitating forms and a few lime-secreting types such as *Solenopora* which deposited lime in its cell walls. Locally the lime-precipitating algae were sufficiently abundant to form recognizable layers, bands, or irregular streaks.

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PLATE 2.—ALGAL LIMESTONES FROM THE UPPER LEADVILLE

Figure

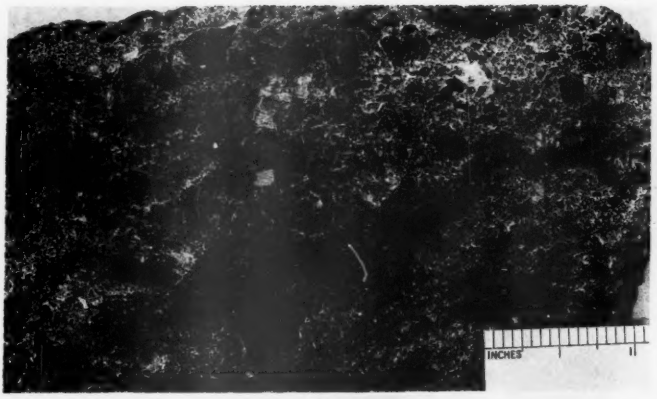
(1) Typical algal-foraminiferal limestone. Lime Creek, Eagle County, Colorado. × ½. Shows dark algal pellets. The light material is foraminiferal.

(2) *Ortonella coloradoensis* n. sp. Glenwood Springs, Colorado. × 37.

(3) Algal-foraminiferal limestone, polished specimen. Richmond Hill, Aspen District, Pitkin County, Colorado. × ⅔. Shows dark algal pellets.

(4) Algal limestone, from the "Algal zone" at Glenwood Springs, Colorado. × 1. Shows irregular white algal colonies.

(5) Algal band around a fossil coral. Express Creek, near Ashcroft, Pitkin County, Colorado. × 1.



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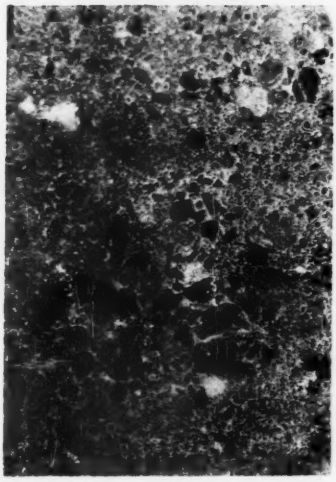

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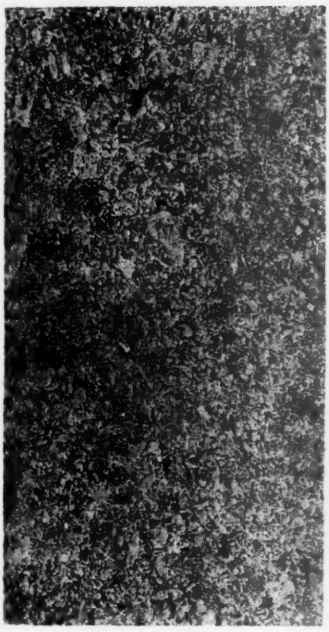

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ALGAL LIMESTONES FROM THE UPPER LEADVILLE

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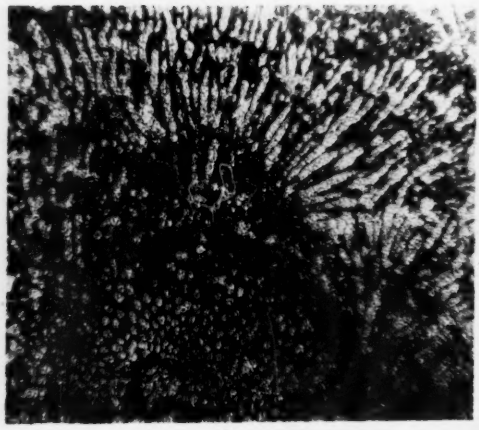

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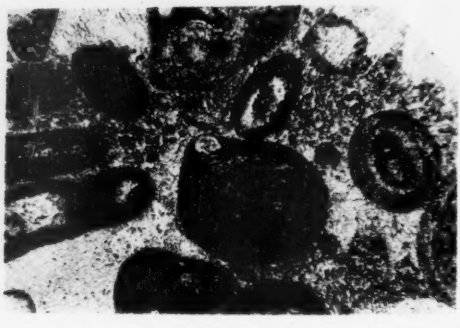

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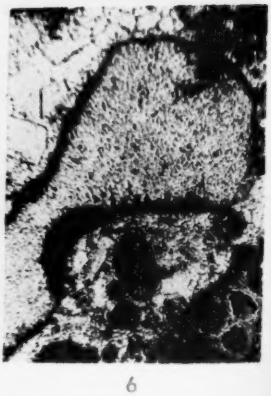

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LEADVILLE CALCAREOUS ALGAE

PLATE 3.—LEADVILLE CALCAREOUS ALGAE

Figure

(1) *Solenopora similis* Paul. Algal zone, Glenwood Springs, Colorado. × 38.

(2) *Garwoodia* aff. *gregaria* (Nicholson). Algal zone, Glenwood Springs, Colorado. × 14.

(3) *Solenopora glenwoodensis* n. sp. Algal zone, Glenwood Springs, Colorado. × 25.

(4) Oölith showing patches and bands of dark algal threads between the bands of needles of light crystalline calcite. Cement Creek, Gunnison County, Colorado. × 37.

(5) Algal pellets of fine threads (black), algal-coated crinoidal debris, and small oöliths. Molds of coarse algal threads form a mottled area in the groundmass. Glenwood Springs, Colorado. × 37.

(6) Crinoidal fragment (white-center) coated and partially perforated by fine algal threads (black). *Endothyra* sp. (below center), bryozoan fragment (lower right) coated and filled with dark algal material. × 37.

PLATE 4.—LEADVILLE CALCAREOUS ALGAE

Figure

(1) *Girvanella ? nicholsoni* (Wethered), *Ortonella media*, and *Garwoodia* sp. Glenwood Springs, Colorado. × 37.

(2) *Garwoodia media* n. sp. Shows well-defined walls. A foraminifer (*Endothyra*) at base of colony. Glenwood Springs, Colorado. × 37.

(3) *Garwoodia media* n. sp. Shows characteristic branching and well-defined walls. Glenwood Springs, Colorado. × 30.

(4) *Ortonella* cf. *kershopensis* Garwood. A typical colony. Glenwood Springs, Colorado. × 20.

(5) *Spongiostroma* sp. ? Molds of coarse algal threads in the groundmass. Fine threads form the dark coating around the white crinoid fragment (top center). Dark algal threads coat and penetrate the large crinoidal fragment at base. Glenwood Springs, Colorado. × 37.

(6) *Ortonella furcata* Garwood. Glenwood Springs, Colorado. × 40.

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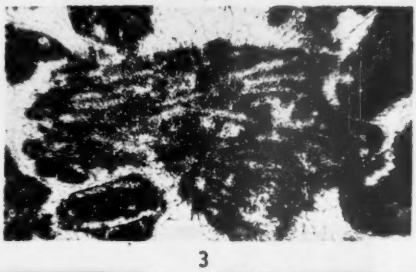

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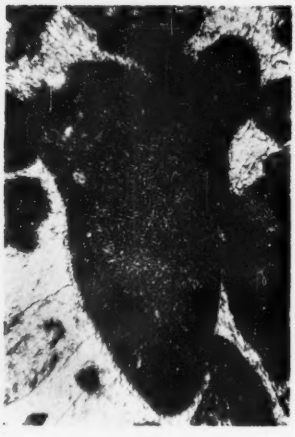

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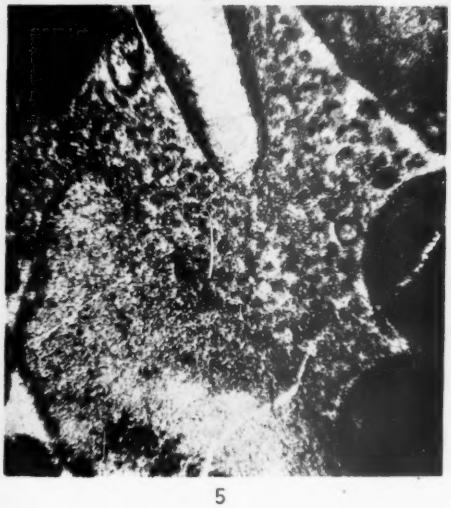

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LEADVILLE CALCAREOUS ALGAE

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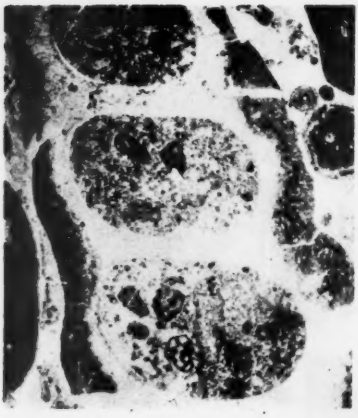

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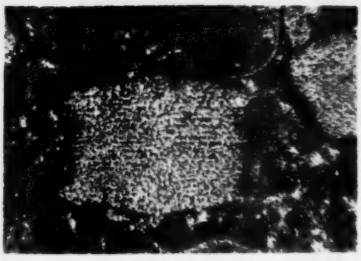

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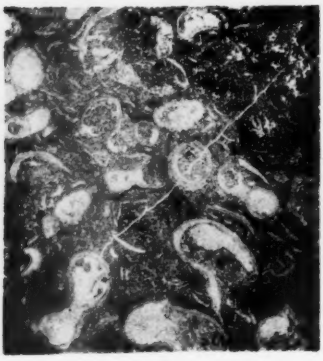

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ALGAE AND ASSOCIATED ORGANISMS

PLATE 5.—ALGAE AND ASSOCIATED ORGANISMS

Figure

(1) Bryozoan shred (center) and crinoidal fragments (white) coated with fine, dark, algal threads. Black algal pellets. Groundmass coarsely crystalline calcite. Meredith, Colorado. × 37.

(2) Bryozoan shred (upper left) and crinoidal fragment (lower left) coated with fine, black, algal threads. Glenwood Springs, Colorado. × 37.

(3) Gastropod, dark algal threads perforating the shell. Foraminifera and dark algal pellets in chambers. Sweetwater Lakes, Colorado. × 20.

(4) Fragment of an echinoid spine, ostracod test (upper right center), and crinoidal fragment (upper right) in algal groundmass. Glenwood Springs, Colorado. × 20.

(5) Ostracod algal limestone. Colorado River at Garfield-Eagle County line, Colorado. × 10.

(6) *Spongiostroma* algal colony (bottom), echinoid spine cross section (left center), Foraminifera, algal-coated crinoidal fragment (upper left). Glenwood Springs, Colorado. × 37.

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GEOLOGY OF THE WALLIS ISLANDS

BY HAROLD T. STEARNS

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ABSTRACT

The Wallis Islands comprise Uvea, the main island, and 22 islets enclosed by or lying upon a nearly circular barrier reef about 200 miles west of the Samoan group in the Southern Pacific Ocean. The highest point in the group, about 470 feet above sea level, and several crater lakes exist on Uvea Island.

The high islands are composed of olivine basaltic lavas and pyroclastics, except for one cinder cone and its associated flows of oligoclase andesite on Uvea Island. The low islands either are composed of calcareous sand or are erosional remnants of tuff cones and lava domes.

Uvea Island was built by the coalescence of lava flows from 19 volcanic vents. The vents comprise 15 flat shield-shaped lava cones, 3 consolidated ash cones, and 1 cinder cone. Except for two Recent lava cones barely covered with soil, the bulk of the island is composed of deeply weathered middle

Pleistocene(?) volcanics. Lavas of intermediate age do not exist. Limestone ejecta in the tuff cones indicate that the whole group is built on a submerged reef, probably about 180 feet below sea level. This reef presumably rests on a Tertiary basaltic volcano. Definite evidence of emerged shore lines at 25 and 5 feet above mean sea level exists, as well as evidence suggestive of higher stands.

INTRODUCTION

This paper is based upon a week's field work in April 1943 when investigations were made for the Navy Department (Stearns, 1943). A network of good roads on the main island of Uvea (also spelled Uea) greatly expedited field work. The smaller islands were visited by boat or were examined from a low-flying plane.

The only previously published geologic description, so far as is known to the writer, is a brief account by De la Rüe (1935). He recognized a dozen or more vents surmounting broad low cones of olivine basalt which overlapped to build Uvea Island, and pointed out the freshness of certain flows to the south in contrast to the deep lateritic weathering over most of the island. The existence of crater lakes was mentioned, and the basin of Lake Lalolalo was briefly described. Nukuloa, Luaniva, Fugalei, and Nukuatea islands also were listed as basaltic. Nukuhifala and Faioa islands were listed as coralline.

GEOGRAPHY AND TOPOGRAPHY

The Wallis group lies between 176° 6′ and 176° 14′ W. Long., and 13° 12′ and 13° 24′ S. Lat. in the Pacific Ocean about 200 miles west of the Samoan group (Fig. 1). It comprises the main island of Uvea and 22 smaller islands and rock islets, all enclosed by a barrier reef (Fig. 2). Uvea, 8½ miles long and 4½ miles wide, has an area of 23 square miles (Fig. 2). Gahi is the only port now in use, although prior to World War II Mata Utu was the main port. The island is composed of broad low volcanic domes which merge imperceptibly to form an undulating plateau (Pl. 1, fig. 1). The Polynesian natives dwell chiefly on sand flats along the shore. The highest point is Mt. Lulu, altitude about 470 feet, near the center of the island. Lakes and marshes occupy six craters. The most spectacular is deep Lake Lalolalo which has not been sounded. It is bounded by sheer rock walls 137 feet high. Red-brown soils cover most of the island to a depth of 8 feet or more. No streams exist, and gullies are scarce even though rainfall averages 100 inches a year. Patches of coral are common in the lagoon, the deepest part of which is 27 fathoms. Ocean-going vessels enter it through Honikulu Pass at the southern end of the barrier reef.

EMERGED SHORE LINE

The 5-foot and 25-foot emerged shore lines are definitely established by marine deposits and abandoned sea caves at these levels. They are known to be eustatic from studies elsewhere (Stearns, 1935; 1941).

The 5-foot shore line is the later. As the sea receded from this strand it left the wide emerged coral sand flats 5–6 feet high which skirt much of the northern and western shores of Uvea (Fig. 2). Abandoned sea caves 5 feet above sea level are numerous at Utuloka Point and in the high islets. A pinnacle of basalt 7 feet high

just off the point on the east side of Mua Bay has fossiliferous reef limestone clinging to it 5 feet above mean sea level (Pl. 1, fig. 2). Fossiliferous marine conglomeratic

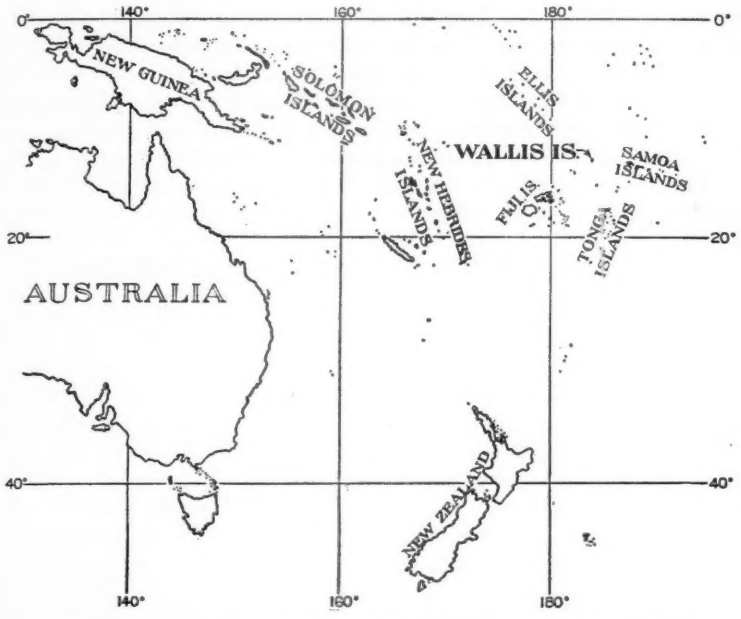

FIGURE 1.—*Map of the southwestern Pacific Ocean showing location of the Wallis Islands*

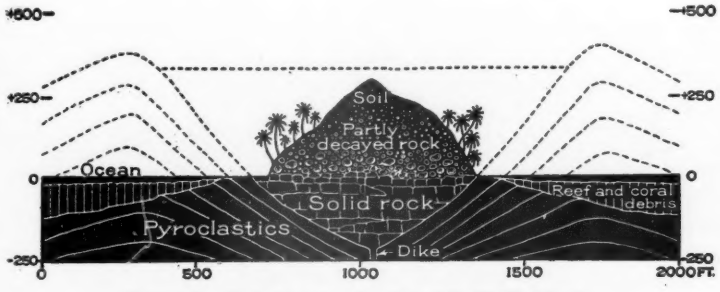

FIGURE 2.—*Geologic map and section of the Wallis Islands*

limestone 4 to 5 feet above present sea level caps pinnacles along the shore of Fugalei Island and crops out in the eastern end of Nukufetau Island.[1]

Several sea caves with their floors about 25 feet above sea level were found on Fugalei Island. Near Utuloka Point on Uvea, at the 25-foot level, is a sea cave 40 feet across.

[1] Nuku means island, but island is added for the benefit of readers not familiar with Polynesian terms.

A terrace, possibly wave-cut, lies about 70 feet above sea level on the northern slope of the hill forming the southern half of Nukuatea Island.

Groups of well-rounded basaltic boulders lie at an altitude of 100 feet half a mile northwest of Alele and half a mile north of Waimalau. They owe most of their rounding to spheroidal weathering, but their exposure at the surface in flat areas free from stream erosion is suggestive of soil stripping by a stand of the sea at this level. These boulder patches resemble those at Mua where the 25-foot sea exposed the residual boulders in a deeply weathered lava flow. Spheroidal boulders exposed 250 feet above sea level north of Mt. Lulu also may indicate soil stripping by the sea. The evidence of the 100-foot and higher stands of the sea is suggestive rather than conclusive.

GENERAL CHARACTER AND AGE OF THE ROCKS

The volcanic rocks of the Wallis group consist of lava flows, pyroclastics, and dikes. With the exception of the oligoclase andesite of the cinder cone and associated flows at Utuloka Point, Uvea Island, all the volcanic rocks consist of olivine basalts and palagonitic tuff. A detailed petrographic description of the rocks is given in the accompanying paper by Macdonald. The volcanics were erupted from 26 closely spaced vents, of which 19 are on Uvea Island. Fifteen of those on Uvea are broad, gently sloping lava cones, three are tuff cones, and one is a cinder cone. The flows range in thickness from 5 to 150 feet or more. They solidified with low dips, seldom more than 2°. Both aa and pahoehoe flows are present, and they resemble the basalts in the Hawaiian Islands. The very thick flows resulted from pooling on flat surfaces or in depressions. Craters indent the summits of the cones where collapse followed the eruption of the lava. Some craters were enlarged by explosions caused by the ingress of ground water at the time of collapse.

The palagonitic tuffs are well bedded and are typical of those produced by paroxysmal phreatomagmatic explosions. They consist of vitric-crystal tuff containing various amounts of accessory and accidental lapilli and blocks. Alteration to palagonite changes them from gray to yellow brown; laterization changes them from brown to red.

The marine sedimentary rocks are loose calcareous beach sand, conglomeratic limestone, and fringing and barrier reefs. All are products of marine organisms. Silty terrigenous sediments occupy depressions such as the Lake Kikila basin.

Marine fossils in the limestone of the 5-foot stand of the sea are too recent to be indicative of the age of the islands. The 25-foot shore line is generally accepted as late Pleistocene in age. Weathering has been slight since that shore line. The Lalolalo and Lanutavake lavas are fairly young and carry a foot or less of soil. They are assigned to the Recent as the 25-foot shore line has not been found on them. Decomposition of basalt proceeds rapidly under the humid tropical climate of the Wallis Islands. The older lavas on Uvea are weathered to lateritic soil to a depth of 10 to 20 feet, and partial decomposition extends to a depth of 50 feet or more. They are assigned tentatively to the middle Pleistocene(?) on the basis of the depth of soil. Subsequent study of the fossil limestone ejecta in the tuff cones may aid in dating the volcanics.

MIDDLE PLEISTOCENE(?) VOLCANIC ROCKS

TUFF CONES

Remnants of tuff cones battered by the sea form Nukutapu No. 2, Nukuatea, Haofa, Nukuafo, Nukutaakimua (Sail Rock), Nukulaelae, and Nukufutu islands (Fig. 2).

Nukufutu and Nukulaelae islands projecting through the northern end of the barrier reef are remnants of a tuff cone. Nukufutu forms a local landmark because of the tall pinnacle on its north side. Tuff, striking N. 60° W. and dipping 50° NE., is exposed on the southwest shore of Fugalei Island. On the southeast shore the strike is N. 15° W., and the dip 25° W. On the northwest shore the strike is N., and the dip 5° E. The tuff contains limestone ejecta. These beds are interpreted as indipping beds of the crater of a tuff cone eroded away by the sea. Fugalei Island is the circular mass of basalt that formerly filled the crater (Fig. 3). No exposures of tuff were found on the shore of Luaniva Island, but it appears to be a similar crater fill of lava.

Nukuatea Island is a doublet tuff cone. The southern half is the remnant of the northern rim of a crater with typical indipping and outdipping beds. Haofa Islet is a part of the southern cone and contains tuff dipping 20° NE. Nukutaakimua Islet (Sail Rock) is a pinnacle of tuff 20 feet high that may be a remnant of an independent cone. The northern part of Nukuatea Island consists of the eastern rim of a tuff crater. Lava lies along the eastern shore and also forms two unnamed islets off the western shore. The lava in these islets contains xenoliths of dunite. Nukutapu Islet No. 2 is a remnant of the northern rim of the same crater isolated by marine erosion. Nukuafo Islet is a remnant of the western rim of a tuff cone. The tuff contains blocks of accessory ejecta a foot across.

The tuff cones on Uvea Island lie at Lano, Mata Utu, and Gahi (Fig. 2). The cone at Lano rises 400 feet above the sea, and the crater is occupied by Lake Alofivai, a fresh-water lake. It has the shape of a horseshoe, opening seaward. The palagonitic tuff in the cone has been extensively quarried for road metal (Pl. 1, fig. 3). Limestone ejecta can be found in the tuff. A road cut near the northern rim exposes 8 feet of decomposed highly vesicular olivine basalt pahoehoe resting on 2 feet of hill wash, 1 foot of baked red soil, and 6 feet of decomposed tuff. The contact strikes N. 70° E. and dips 20° S. Either lava was erupted later in this cone or lava from Afana Crater spilled into the crater. The latter seems likely as 25 feet of weathered basalt from Afana Crater caps the western rim of the cone.

Most of the tuff cone at Mata Utu has been cut away by the sea. Only a narrow weathered remnant half a mile long and 60 feet high remains.

The tuff cone at Gahi is indented with 5 coalesced craters. The largest craters open northeastward to the sea and shelter the port of Gahi. The vents are not contemporaneous as 25 feet of decomposed lava on the southern slope rests on 8 inches of red soil and lapilli-sized lithic-vitric tuff containing fragments of an older tuff. The lava on the southwestern slope is rotted to a depth of 40 feet. The tuff is well exposed at Utuhamia Point, a rim of one of the craters, as shown by the beds dipping northward and southward 18° from the crest of the ridge forming the point. At

this place ejecta of reef limestone 6 inches across and gabbro and dunite fragments are common. A block of basalt 18 inches across containing dunite and feldspathic xenoliths was found also. Fragments of older tuff also are present among the ejecta. These ejecta are described by Macdonald.

The tuff cones are older than the surrounding lavas and were formed by paroxysmal explosions resulting from hot magma coming in contact with ground water or sea water. All contain coralliferous limestone ejecta indicating that they erupted through reef.

CINDER CONE AT UTULOKA POINT

An erosional remnant about 240 feet high of a typical cinder cone forms Utuloka Point on Uvea Island (Pl. 2, fig. 1). The cinders are suitable for road metal and are well exposed in the 120 foot sea cliff on its eastern side. The erupting magma was an oligoclase andesite, as determined from a specimen collected from a thin sheet of dense lava interbedded with the cinders. This vent erupted the only andesite found in the Wallis Islands.

LAVA CONES AND FLOWS

Afana, Ghost, Lulu, McKee, Hill 305, Lanituli, Lanumaha, and one unnamed cone constitute the middle Pleistocene(?) lava cones on Uvea Island. McKee Hill and Hill 305 are the only ones without craters. The largest, Mt. Lulu, is about 470 feet high. An excavation in the rim of Lanituli shows 2 feet of rotted lithic tuff, probably from Lanutavaki Crater, resting on 2 feet of coarse cinders and thread-lace scoria. Under the scoria is the crust of a vesicular pahoehoe flow.

All the middle Pleistocene(?) lava cones are deeply weathered; hence, exposures are scarce. No attempt was made to map their flows, as they merge with one another. Lake Kikila occupies a broad depression formed by the merging of flows from several cones. The lava in the northern end of the island is coarser than the other basalts. This may be due to slow cooling of lava pooled on a flat, or it may indicate basalt older than any of the cones. The coarser basalt is found only in large spheroidally weathered boulders.

The lava cones resemble those on the Snake River Plain of Idaho (Stearns, Crandall, and Steward, 1938, p. 7) and Kane Nui o Hamo on Kilauea Volcano, Hawaii. Near the summit, they contain thin beds of spatter and cinders interbedded with lava. Fineveke Hill on Uvea Island is covered deeply with soil; its form suggests a cinder pile on a lava cone.

A sea cliff 150 feet high at Lausikula Point just south of Utuleve exposes 40 feet of bedded spatter, cinder, and highly vesicular lava. The hill just inland appears to be the eastern part of a cone; the western part was destroyed by marine erosion.

Thin-bedded decomposed cindery pyroclastics, containing a few blocks of olivine basalt reaching 6 inches across, are exposed in Mt. Olaliki.

Nukufetau Island is composed of beds of vesicular lava and cinder. It is the only island of this type. It is the remnant of the northern rim of a cone which has been destroyed by the sea.

FIGURE 1. LOOKING NORTH TOWARD GHOST AND AFANA CONES FROM UTULOKA POINT
Showing native village on the sand flat along the shore.

FIGURE 2. PINNACLE OF BASALT SOUTH OF GAHI, UVEA ISLAND
Hammer is pointed to fossiliferous marine limestone.

FIGURE 3. QUARRY NEAR LAKE ALOFIVAI IN PALAGONITIC TUFF

CONES, EMERGED LIMESTONE, AND QUARRY, UVEA ISLAND

FIGURE 1. LOOKING NORTH AT LOW TIDE ACROSS SHORE FLAT CUT IN ANDESITE AND VENEERED WITH CALCAREOUS SAND
Cinder cone at Utuloka Point in the background.

FIGURE 2. AIR VIEW OF LANUTAVAKE, CRATER LAKE, FROM AN ALTITUDE OF 8000 FEET
The crater lakes of Lanituli and Lanumaha are also visible.
(*Photo by U. S. Marine Corps.*)

FIGURE 3. EAST WALL OF LALOLALO CRATER

SHORE FLAT AND LANUTAVAKE AND LALOLALO CRATERS, UREA ISLAND

RECENT VOLCANIC ROCKS

LANUTAVAKE BASALT AND VENTS

The Lanutavake basalt extends across a narrow neck near the southern end of Uvea Island (Fig. 2). It is an olivine basalt pahoehoe poured from a lava cone indented by two craters. The northern and larger crater is occupied by Lake Lanutavake[2] (Pl. 2, fig. 2). The southern one is dry because its bottom is above the basal water table, which lies close to sea level.

A narrow tongue of the lava extends to the western shore half a mile north of Halalo. It is 4 feet thick and rests on 6 feet of soil and 20 feet of decomposed olivine basalt pahoehoe. It overwhelmed a forest, as shown by the numerous tree molds in it. The basalt has been extensively quarried for road metal 1 mile north of Gahi (Fig. 2).

The altitude of the rim of Lanutavake Crater is 221 feet. The altitude of the surface of the fresh-water lake in it is 27 feet. Exposed in the eastern wall is 20 feet of lithic explosion debris overlying beds of vesicular-banded olivine basalt 30 to 75 feet thick with a little spatter on top. Tree molds are numerous where the basalt rests on 6 feet of red soil. The upper 4 feet of the soil is baked. The small amount of decomposition on the surface of the lava and the fact that it buried deeply rotted lavas indicate a considerable time interval between the Pleistocene(?) and Recent eruptions.

The 20 feet of coarse lithic tuff resting directly on fresh lava on the crater rim indicates that ground water rushed into the vent and induced short-lived explosions when the lava outpourings ceased and the magma column subsided, causing collapse.

LALOLALO BASALT AND VENTS

The Lalolalo olivine basalt covers most of the western promontory of Uvea Island and forms a flat lava cone around the three source craters. The altitude of the rim of the northern crater is 110 feet and of Lake Lano in its floor, 2 feet. The altitude of the rim of the southern crater is 137 feet and of Lake Lalolalo in its floor, 4 feet. The middle crater is about 75 feet deep and dry.

Both pahoehoe and aa were poured from these vents. The margin of the basalt on the eastern side forms a bluff 20 feet high. Lake Lalolalo is bordered by a vertical wall which the writer descended on the long roots of a banyan tree. The wall on the western side consists of three lava beds with a 4-foot bed of lapilli cinder 40 feet above the lake. Several flow units are faintly discernible in the eastern wall, but no cinders (Pl. 2, fig. 3). Two feet of soil and large scattered blocks on the crater rim presumably indicate a short-lived explosion at the time of collapse. The soil may be decomposed ash. Lano Crater has on its rim 3 feet of lithic tuff containing fragments of basalt 6 inches across, indicating a phreatic explosion at the time of collapse. Under the tuff is 20 feet of basalt with parallel 3-inch bands of highly vesicular rock.

The thin soil on the Lalolalo basalt indicates that it is essentially contemporaneous with the Lanutavake basalt.

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[2] Lanu means lake, but lake is added for the benefit of readers not familiar with Polynesian terms.

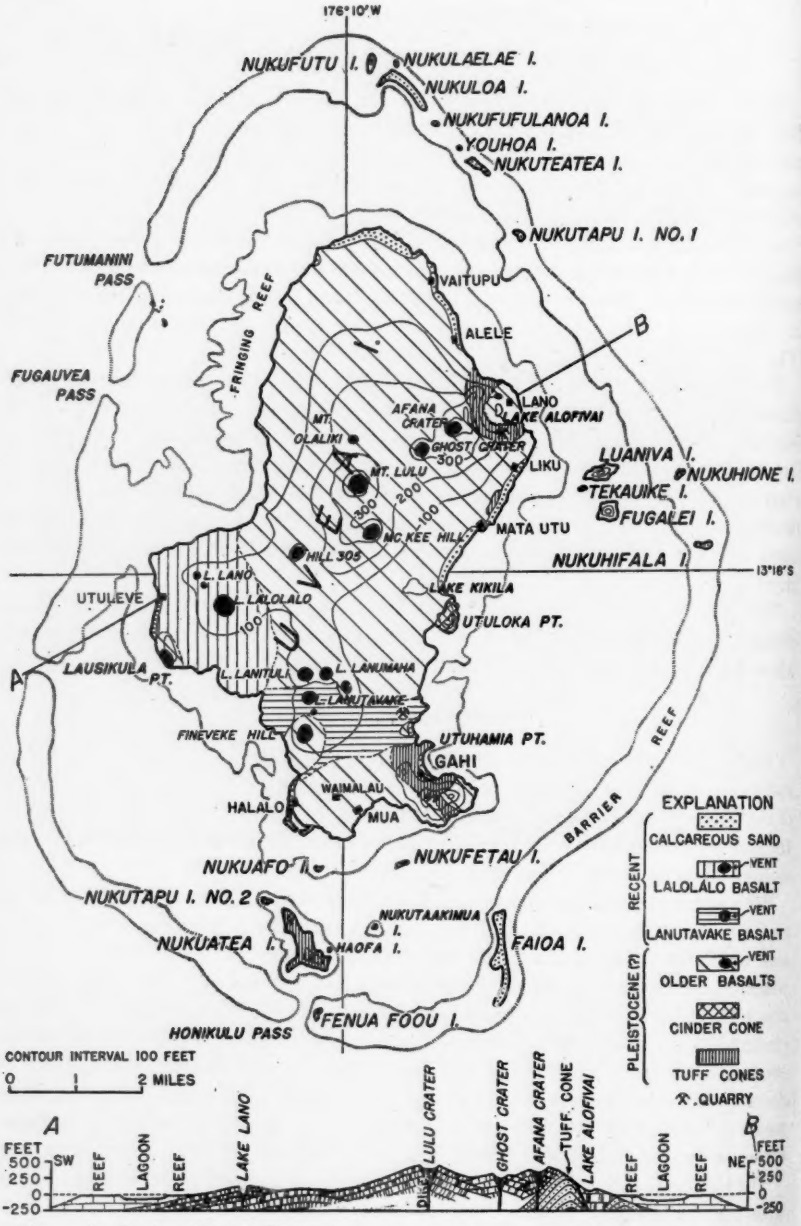

FIGURE 3.—*Section of Fugalei Island showing interpretation of crater fill in an eroded tuff cone*

The solid basalt of the crater fill grades upward into partly decayed basalt and soil.

INTRUSIVE ROCKS

Only four dikes were found. One of platy vesicular olivine basalt, 8 inches wide, cuts N. 50° W. through Olaliki cone on Uvea Island. A 5-foot basalt dike striking about N. 80° W. cuts the eastern tip of Nukuatea Island. Two 2-foot basalt dikes striking about N. 40° W. are exposed in the northern end of Nukutapu Island No. 2.

RECENT SEDIMENTARY ROCKS

CALCAREOUS SAND AND GRAVEL

Loose calcareous sand beaches form narrow strips at Halalo and Utuleve on the west coast of Uvea Island and on most of the east coast north of Utuloka Point (Pl. 1, fig. 1). The sand is composed of Foraminifera and comminuted shells and coral. It is the so-called coral sand of the tropics. It forms also Fenua Foou, Faioa, Nukuhifala, Nukuhione, Nukutapu No. 1, Nukuteatea, Youhoa, Nukufufulanoa, and Nukuloa islets on the barrier reef. Most of these islets have coral cobble beaches.

FRINGING REEF AND FRINGING BENCHES

A fringing reef varying from a few feet to half a mile in width skirts the island of Uvea. It is exposed at low tide and is traversible by jeep. At high tide the reef is submerged to a depth of 3.5–4.5 feet. Living corals are practically absent. The reef is chiefly consolidated coral sand. It appears to be largely the beveled reef of the 5-foot sea. It is so nearly flat that its outer edge is seldom as much as 6 inches lower than its inner margin.

Corals thrive in the shallows between the fringing reef and the barrier reef of the lagoon, forming coral knolls and knobs. Beautiful corals can be seen in the shallow water near the Leper Colony on Nukuatea Island.

In places, remarkably wide fringing benches are cut in the lava. One such bench lies half a mile south of Utuloka Point on Uvea Island. The hard lava rock surface is 300 feet across and lies about 6 inches above low tide (Pl. 2, fig. 1). It is covered with a small variety of mussel. At this place a nearly horizontal lava flow weathered to a depth of 25 feet extended into the sea with the bottom of the zone of weathering coinciding with sea level. The 5-foot sea and the present sea removed the soil and laid bare the underlying hard rock.

A similar bench lies on the south side of Luaniva Islet. Pinnacles of rock rise above the general level of the bench and are capped with fossiliferous limestone 4 feet above sea level, indicating that the present sea is dressing down a bench formed during the 5-foot sea.

BARRIER REEF

Encircling Uvea Island about 2 miles off shore is a nearly continuous living barrier reef which is partly exposed at low tide (Fig. 2). It is corrugated by thousands of narrow shallow channels where the waves surge in and out. Some channels are

lined with yellow sand and stand in strong contrast to the adjacent dark-brown reef. Soundings in the lagoon indicate that the reef rises from a platform about 180 feet below sea level, in common with many barrier reefs in the Pacific. Outside the barrier, dark-blue water indicates that the ocean floor drops rapidly.

STRUCTURE

The alignment of the Recent craters and the trend of the few dikes exposed indicate that many of the volcanic fissures trend northwest-southeast, in common with the dominant rifts of the adjacent Samoan Islands (Stearns, 1944, p. 1328). Lulu, Ghost, Afana, and Alofivai craters lie in a northeast-southwest line suggesting cross fissures. No evidence of faulting or folding was found.

GEOLOGIC HISTORY

The flat dips in the lavas of Uvea Island indicate conclusively that they were erupted on a pre-existing platform. In this respect they differ from the adjacent Alofi and Futuna (Horne or Hoorn) Islands and the Samoan Islands whose lavas dip 10° to 25° seaward from their respective vents. The limestone ejecta in the tuff cones indicate that the underlying platform is a submerged reef. An extensive drowned barrier reef surrounds Tutuila, Samoa, at a depth of 30 fathoms (Chamberlin, 1924; Stearns, 1944, p. 1309), corresponding in depth to the platform from which the barrier reef of the Wallis Islands rises. It is believed that the well-formed barrier reef encircling the Wallis Islands was able to develop in the rapidly fluctuating seas of the late Pleistocene because of the existence of the gently shelving shore made by the low-dipping Pleistocene(?) lavas and the lack of streams on Uvea. Conditions are similar to those on the coast of Upolu Island where a barrier reef thrives (Stearns, 1944, p. 1328).

The substructure of the Wallis Islands is believed to be a basaltic volcano built from the ocean floor to about present sea level during the Tertiary. It was beveled by the eustatic low stands of the sea during the early ice age and veneered with a reef. Eruptions during the middle Pleistocene(?) built the present Wallis Islands. The presence of oligoclase andesite indicates that the magma reservoir entered the third phase of volcanism in the middle Pleistocene(?) (Stearns, 1940). Subsequent eustatic rise and fall of the sea has destroyed some of the cones and cliffed the higher islands. Little reef grew during the 100-foot(?), 25-foot, and 5-foot stands of the sea. A eustatic low stand of the sea is known to have preceded the 25-foot sea and probably during this time most of the cliffing was done, as the barrier reef was probably dead or decadent at that time.

In late geologic time, in common with other mid-Pacific islands, the Wallis Islands entered the fourth phase of volcanism, and the Lalolalo and Lanutavake basalts were erupted. The present barrier reef is the relic of the barrier reef that grew upward from the 30-fathom platform in the late Pleistocene, 25 feet having been eroded away since the last high stand of the sea which corresponded to the last interglacial epoch.

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PETROGRAPHY OF THE WALLIS ISLANDS

BY GORDON A. MACDONALD

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ABSTRACT

The lavas of Uvea Island, in the Wallis group, include olivine basalts containing colorless monoclinic pyroxene, less abundant olivine basalts containing titaniferous pyroxene, and oligoclase andesite. Palagonite tuff builds cones along the eastern coast. Of the lesser islands in the Wallis group, Nukuatea is built largely of palagonite tuff, with a flow of olivine basalt; Nukufetau is composed of olivine basalt flows and cinders; Luaniva is composed largely of olivine basalt with a little tuff; and Fugalei of olivine basalt which filled the bowl of a tuff cone, most of which has been eroded away. Other islets represent the emergent edge of the barrier reef and are composed of poorly to well-consolidated calcareous sand. The lavas of the Wallis Islands belong to the alkaline suite of the central Pacific volcanoes, rather than to the calc-alkaline suite of the circum-Pacific belt.

INTRODUCTION

The Wallis Islands lie in the southwestern part of the Pacific Ocean, 220 miles west of the island of Savaii, in the Samoan group, and 480 miles northeast of Suva, on Viti Levu Island in the Fiji group (Fig. 2). They center approximately at Long. 176° 10′ W., and Lat. 13° 18′ S. The central and largest island of the group, Uvea,

is 8.5 miles long and 4.5 miles wide, with an area of about 23 square miles. The highest point on Uvea is about 470 feet above sea level. Besides Uvea, the Wallis group includes 22 other, much smaller islands, some of them volcanic, but most of them representing emergent parts of the barrier reef. Only the islands of volcanic origin are discussed in the present paper.

The petrographic study is based on specimens collected by H. T. Stearns, of the U. S. Geological Survey, in May 1943. In all, 51 specimens have been examined, 41 of them in thin section. Their localities are shown on Figure 1. All but six are from the main island of Uvea. Three are from Nukuatea Island, and one each from Nukufetau, Fugalei, and Luaniva islands. The composition of the feldspars has been determined by extinction-angle and immersion methods. The optic axial angles in pyroxenes have been estimated from optic-axis or acute-bisectrix interference figures.

The writer wishes to thank H. T. Stearns for access to the material and for criticism of the manuscript. The brief sketches of the general geology which are included as a background to the petrographic discussion are based on the foregoing paper by Stearns (1945). The writer has not visited the Wallis Islands.

PREVIOUS INVESTIGATIONS

Little previous work appears to have been done on the petrography of the Wallis Islands. The lavas of Uvea were stated by De la Rüe (1935) to be olivine basalts of great lithologic uniformity. A specimen of basalt from Uvea has been chemically analyzed by Raoult and studied by Lacroix (1940), but publication of the analysis and petrographic description appears to have been delayed, presumably by the war. Lacroix states that the rock contains 0.71 per cent of normative free silica and that the proportion of anorthite in the normative feldspar is 55 per cent.

GENERAL GEOLOGY

The island of Uvea has been formed by lava flows and associated pyroclastic rocks from 20 closely spaced vents (Fig. 1). Fifteen of these are broad, gently sloping shield volcanoes, four are tuff cones, and one is a cinder cone. Interfingering and overlapping of lava flows from the shield volcanoes has built a gently undulating plateau, with only slight topographic relief. Collapse at the summit of several of the shields has formed nearly circular craters with precipitous sides, which contain lakes or swamps. No perennial streams exist, and the terrane is almost undissected. Most of the lava flows are old and deeply weathered, decomposition commonly extending to depths of 50 feet or more. However, the flows from Lalolalo and Lanutavake craters are quite young, probably not more than a few thousand years old, and are covered with only a foot or less of soil.

Along the eastern shore, at Lano, Mata Utu, and Gahi, are cones of moderately to well-consolidated tuff, containing fragments of underlying lava flows and reef limestone. In the formation of these cones the rising magma encountered rock saturated with water, and there resulted violent explosions, building cones resembling Diamond Head and Punchbowl on Oahu in the Hawaiian Islands. The term "phrea-

FIGURE 1.—*Map of the Wallis Islands, showing specimen localities*

tomagmatic" has been suggested for this type of volcanic explosion (Stearns and Vaksvik, 1935, p. 15–16). In contrast, the building of the cinder and spatter cones involves no contact of the magma with extraneous water, but simply the more or less explosive fountaining of the magma itself. A cinder cone of this type is situated at Point Utuloka, on the eastern shore of Uvea.

The small outlying islets of the Wallis group are of two general types: those of volcanic origin and those composed of calcareous sand. Among the volcanic islets, Nukuatea, Nukutapu No. 2, Haofa, Nukuafo, Nukuaakima, Nukulaelae, and Nukufutu are remnants of tuff cones; Luaniva and Fugalei appear to be remnants of tuff cones which contained congealed lava lakes in their craters; and Nukufetau is a remnant of a cinder and lava cone. The sand islands represent emergent parts of the barrier reef and include Fenua Foou, Faioa, Nukuhifala, Nukuhione, Nukutapu No. 1, Nukuteatea, Youhoa, Nukufululufulanoa, and Nukuloa. The sand ranges from unconsolidated to well cemented.

UVEA ISLAND

LAVAS

General features.—The lavas of Uvea may be divided into three general types. Nearly all are olivine basalts, which may be separated into two subtypes on the basis of the pyroxene they contain. In one, the pyroxene is colorless, with weak dispersion; the other contains purplish titaniferous augite with moderately strong dispersion. Gradations between these two types may occur but are not represented in the suite of specimens studied by the writer. The third type is oligoclase andesite, which has been found only among the lavas associated with the Utuloka cinder cone. Table 1 lists the composition of each of the specimens, and the localities at which the specimens were collected are shown in figure 1.

Basalts with colorless pyroxene.—By far the most abundant lavas on Uvea are the basalts containing colorless pyroxene. The various flows of this type are too similar in composition and texture to warrant their individual description. They range from dense to highly vesicular and include both aa and pahoehoe. Some specimens are nonporphyritic in hand specimen, but most contain scattered to moderately abundant megascopic phenocrysts of olivine. Even those which are megascopically nonporphyritic contain numerous intratelluric microphenocrysts of olivine. Only in specimen 20, from the top of McKee Hill, are the olivine phenocrysts entirely unresorbed and unaltered. In most specimens they are partly resorbed, or partly altered, and in many they show both resorption and alteration. Resorption varies from merely a slight rounding of corners in some rocks to extensive rounding and embayment in others. In some rocks the partly resorbed phenocrysts are surrounded by a narrow border of finely granular exsolved iron ore. In most specimens the olivine phenocrysts are altered around the edges to iddingsite, but in two (number 18, a 6-inch ejected block from the top of Olaliki Cone, and number 51, a specimen of basalt from Lano cone collected on the eastern shore) they are partly altered to serpentine. Specimen 21, from the southern rim of Ghost Crater, and specimen 31, from the northwestern rim of Lanumaha Crater, contain partly resorbed olivine phenocrysts altered around the edges to iddingsite, and enclosed in thin rims of fresh second-generation olivine which were deposited at the time of crystallization of the groundmass (Edwards, 1938; Macdonald, 1940 B, p. 155–156).

Microphenocrysts of plagioclase are present in many specimens, grading in size into the groundmass. Macrophenocrysts of feldspar have been found only in spec-

imen 36, collected from a residual boulder a quarter of a mile northwest of Lake Kikila, which contains moderately abundant lath-shaped crystals of labradorite. The same specimen contains microphenocrysts of colorless augite, with $+2V = 55°$. The only other specimen which contains microphenocrysts of pyroxene is number 52, from the western slope of Hill 305. The flow from which specimen 36 was collected may also have come from the Hill 305 vent. In specimen 52, from Hill 305, the pyroxene microphenocrysts consist of a core of augite, with $+2V = 55°$ and weak dispersion, surrounded by a shell of pigeonite, averaging about 0.03 mm. thick, in which the extinction angle and optic axial angle are smaller than in the core.

Intersertal and intergranular groundmass textures are about equally abundant, and a few specimens show variations from one to the other within a single slide. The minerals of the groundmass include plagioclase, colorless monoclinic pyroxene, olivine, and iron ore. In the intersertal lavas the interstices are occupied by colorless to pale-brown glass, and in specimen 51 by a little finely fibrous brownish-green chloritic material. In all specimens but one, the dominant feldspar is intermediate labradorite. The single exception (number 37) was collected on the western rim of Fineveke Crater, and contains sodic labradorite ($\beta = 1.559$). A lava flow from Lalolalo Crater (number 10), collected along the road a quarter of a mile south of Lake Lalolalo, contains, besides abundant intermediate labradorite, small anhedral interstitial grains of labradorite-andesine. Likewise, specimen 16, from a lava flow exposed at the coast near Mata Utu, contains small interstitial grains ranging in composition from sodic labradorite to calcic andesine. In a basalt flow from Mount Lulu, sampled at a pit on the eastern side of that mountain (specimen 17), both microphenocrysts and groundmass plagioclase are largely altered, perhaps by the action of volatiles, to colorless isotropic material probably glass or opal.

In some specimens the grains of colorless monoclinic pyroxene are too small to yield optic interference figures, but in most the pyroxene has been determined as pigeonite. No augite has been identified in the groundmass. The opaque minerals include both magnetite and ilmenite. Both are generally present, but magnetite is more abundant. In a few slides no ilmenite has been recognized. On the other hand, in specimen 32, from the southern rim of Lanituli Crater, and specimen 10, collected a quarter of a mile south of Lake Lalolalo, the opaque mineral is largely or entirely ilmenite.

Biotite has been found in specimen 37, from the western rim of Fineveke Crater, and specimen 38, from a lava flow in the western wall of Lalolalo Crater, 50 feet below the rim. In the latter it forms small pale brown anhedral flakes occupying interstices between the other minerals of the groundmass. The lava from Fineveke Crater contains similar small anhedral interstitial grains, and also larger flakes, some of them as much as 2 mm. across, projecting into vesicles. The larger flakes are strongly pleochroic from straw-yellow to deep reddish-brown, and have $a-2V$ of about 20° and strong dispersion, $r<v$. At both localities the biotite is obviously of very late magmatic or deuteric crystallization, as it is in Hawaiian basalts and andesites (Macdonald, 1940a, p. 68; 1940b, p. 158).

Basalts with titaniferous pyroxene.—Olivine basalts containing titaniferous augite appear to be much less abundant on Uvea than those containing colorless pyroxene.

Stearns' collection contains only five specimens of this type of basalt, and of these at least three, and possibly four, are from flows probably derived from the same vent. The precise location of the vent is, however, in doubt. Residual boulders are scattered over the surface of much of the northern part of the island. Specimens 12 and 13 are from these boulders. Both contain titaniferous augite. Specimen 14, which appears to be from the same flow, was collected at an outcrop on the beach, 0.4 mile northwest of Vaitupu. Specimen 19 is from an outcrop along the road, 0.3 mile northwest of Hill 305. It closely resembles the aforementioned specimens and may have been derived from the same vent.

The four specimens are porphyritic, with moderately abundant phenocrysts of olivine and plagioclase from 1 to 2 mm. long. Specimens 12 and 13 are diktytaxitic (Fuller, 1931, p. 116), with many irregular, miarolytelike cavities resulting from the escape of a residual fluid. In specimens 13 and 19 the olivine phenocrysts show little evidence of resorption and are only slightly altered to serpentine. The olivine phenocrysts in specimen 12 are partly resorbed and partly altered to iddingsite, and those in specimen 14 are largely altered to iddingsite. In specimen 12, the iddingsite is surrounded by thin jackets of fresh olivine. The jackets have slightly higher birefringence than the cores, probably indicating a higher fayalite content in the later-crystallized olivine. The feldspar phenocrysts grade in size into the groundmass. Microphenocrysts of titaniferous augite are present in specimens 14 and 19, but not in the other two. They grade imperceptibly into the groundmass pyroxene.

The groundmass texture is intergranular in specimens 12, 13, and 14, and intersertal in 19. Specimens 12 and 13 are exceptionally coarse-grained for mid-Pacific lavas; the average grain size of the groundmass is respectively 0.5 and 0.4 mm. The same two specimens have diktytaxitic structure, so that the coarse granularity is probably the result of very abundant volatile constituents. The groundmass is composed of intermediate labradorite, purplish titaniferous augite, olivine, iron ores and in specimen 19 a little interstitial glass. The iron ores include both magnetite and ilmenite, with ilmenite the more abundant. The augite has $+2V = 60°$ and moderately strong dispersion. In specimen 12, many grains of augite are zoned, the outer part showing a smaller extinction angle and deeper color than the core. In the holocrystalline specimens, feldspar constitutes about 40 per cent of the rock.

The fifth specimen of basalt containing titaniferous augite was collected at Mua, on the southern coast of Uvea. It contains moderately abundant phenocrysts of olivine and augite, less than 1 mm. long, but none of feldspar. The olivine phenocrysts are unresorbed and unaltered. Those of augite are pale purplish-brown, with $+2V = 55°\pm$, and strong dispersion, $r > v$. They are distinctly zoned, the border having a deeper color, smaller extinction angle, and smaller optic axial angle than the core. In some grains the zoning is of the hour-glass variety. The groundmass is intersertal, composed of intermediate labradorite ($\beta = 1.561$), slightly purplish pigeonite, olivine, magnetite, ilmenite, interstitial glass, and interstitial reddish-brown chloritic material. Many vesicles and interstices are partly or entirely filled with calcite. The pyroxene of this rock, particularly that of the groundmass, is less titaniferous than that of the other specimens.

Oligoclase andesite.—Only two specimens of oligoclase andesite are included in the

collection. One (number 24) is from a dense flow intercalated with the cinders in Utuloka cinder cone. It is macroscopically nonporphyritic but contains microphenocrysts of olivine largely or entirely altered to iddingsite. Feldspar microphenocrysts are zoned from intermediate andesine in the center to calcic oligoclase on the outside. The groundmass is composed largely of anhedral grains of calcic oligoclase ($\beta = 1.547$), enclosed in which are numerous small grains of olivine altered to iddingsite, colorless monoclinic pyroxene, and iron ore. Minute needles of apatite and a few flakes of pale-brown biotite also are present. The iron ore is largely or entirely magnetite.

Specimen 25 was collected from a bench 6 inches above low tide, 0.55 mile southwest of Utuloka Point. The flow probably came from Utuloka cone. The rock contains rare olivine phenocrysts up to 1 mm. long and moderately abundant microphenocrysts of olivine and plagioclase, grading in size into the groundmass. The plagioclase microphenocrysts are zoned from intermediate andesine to calcic oligoclase. The groundmass is intergranular, composed of calcic oligoclase ($\beta = 1.548$), olivine, colorless monoclinic pyroxene, magnetite, and a little ilmenite. A few irregular flakes of purplish-brown biotite occupy interstices between the other minerals. They are of very late crystallization. Minute needles of apatite are quite abundant, enclosed in the feldspar.

The two specimens of oligoclase andesite closely resemble rocks of Tutuila, in the Samoan Islands (Macdonald, 1944b, p. 1337–1339), and of West Maui (Macdonald, 1942, p. 321–323) and Kohala (Washington, 1923, p. 476–482) volcanoes in the Hawaiian Islands.

PYROCLASTIC ROCKS

The Gahi tuff cone, in the southeastern part of Uvea, is formed largely of well-consolidated vitric-crystal tuff, containing abundant accessory and accidental blocks and lapilli. Most of the tuff has been partly or entirely altered to palagonite and is yellowish brown or reddish brown, but in places it is unaltered and is bluish-gray. A sample of the unaltered tuff (number 29) was collected at the northeastern corner of Gahi Bay. It is fine-grained and dense and is composed largely of opaque black glass, with many crystals of olivine and less abundant crystals of feldspar. A few grains of augite are present, apparently derived from the disintegration of gabbro inclusions. The interstices are filled with calcite and a weakly birefringent zeolite. A specimen of altered tuff (number 28) collected near by is composed largely of pumiceous glass, altered to orange-brown palagonite. Most of the palagonite is isotropic, but some of it forms minute fibers with moderately high birefringence. A few phenocrysts of olivine are present. The interstices are filled with colorless material, probably zeolite, partly isotropic and partly in fibrous aggregates with positive elongation, low birefringence, and refractive indices less than 1.54.

Accessory and accidental ejecta in the Gahi tuff cone range from fragments 1–2 mm. across to blocks several feet in diameter. Blocks of olivine basalt, torn from the walls of the conduit where it passes through underlying lava flows, are numerous. Most of them resemble lavas already described, but one (specimen 6) is more mafic than any other rock in the collection. It is a dark-gray dense lava, with a few

phenocrysts of plagioclase and olivine less than 1 mm. long, grading in size into the intersertal groundmass. The latter is composed of intermediate labradorite (β = 1.562), pale purplish-brown pigeonitic pyroxene, olivine, magnetite, ilmenite, and a little glass. Staining by Shand's method (Shand, 1939) revealed no nepheline.

TABLE 1.—*Rock specimens from Uvea Island*
(Localities shown on Fig. 1)

Specimen number	Rock type
1 to 5	Olivine basalt (specimens not collected in situ).
6	Olivine basalt, transitional toward picrite-basalt; essential ejectum in Gahi tuff cone.
7 and 8	Olivine basalt; accessory ejecta in Gahi tuff cone.
9	Palagonite tuff.
10 and 11	Olivine basalt, with colorless pyroxene.
12 to 14	Olivine basalt, with titaniferous pyroxene.
15	Palagonitized vitric-crystal tuff.
16 to 18	Olivine basalt, with colorless pyroxene.
19	Olivine basalt, with titaniferous pyroxene.
20 to 23	Olivine basalt, with colorless pyroxene.
24 and 25	Oligoclase andesite.
26	Coral fragments; accidental ejecta in Gahi tuff cone.
27	Dunite and wehrlite fragments, Gahi tuff cone.
28	Palagonite tuff; inclusions of older tuff in Gahi tuff cone.
29	Vitric-crystal tuff, unaltered.
30 to 32	Olivine basalt, with colorless pyroxene.
33	Same; inclusions in Gahi tuff (?).
34	Palagonitized crystal-vitric lapilli-tuff.
35 to 38	Olivine basalt, with colorless pyroxene.
39	Olivine basalt, with titaniferous pyroxene.
40 to 43	Olivine basalt, with colorless pyroxene.
44	Palagonitized vitric-crystal-lithic tuff.
45 to 50	Specimens from smaller islands near Uvea.
51 and 52	Olivine basalt, with colorless pyroxene.

Only about 30 per cent of feldspar is present, and the rock is thus transitional to the picrite-basalts.

Many fragments of reef limestone, torn by the explosions from the underlying coral reefs, are enclosed in the tuff of the Gahi cone. Also enclosed in the tuff are angular to subangular fragments of gabbro, dunite, and wehrlite.

Specimen 34, from the rim of a slightly older cone just south of and overlapped by the Gahi cone, is a dense buff fine-grained tuff containing numerous lapilli up to 8 mm. long, of yellowish-brown pumice and dark-gray basalt. The tuffaceous matrix is largely brown palagonite, clouded with abundant finely granular iron ore. Small phenocrysts of olivine are scattered throughout. The pumice lapilli are brown glass, locally altered to palagonite, with scattered phenocrysts of olivine and labradorite. The denser lapilli are largely black opaque glass, also containing crystals of olivine and labradorite. Vesicles in the lapilli, and interstices in the matrix, are filled with

a weakly birefringent zeolite, in radiating fibers, with positive elongation, +2V close to 0°, and refractive indices much below 1.54. It is probably natrolite.

The tuff of the Lano and Mata Utu cones is very similar to that of the Gahi Cone and requires no additional description.

LESSER ISLANDS

NUKUATEA ISLAND

Nukuatea, 1.2 miles long and 0.75 mile wide at the widest point, lies about a mile south of Uvea. It is a remnant of two coalescing tuff cones, with a small lava flow on the western side. Three specimens were collected by Stearns on Nukuatea. Of these, two are of the tuff, and one of the lava.

The tuff is a greenish-gray to yellowish-brown dense palagonitic lapilli tuff, containing angular darker-green lapilli up to 6 mm. across. The matrix consists of angular shards of basaltic glass, containing microphenocrysts of olivine and labradorite. The glass is largely altered to palagonite, some of which is isotropic, and some of which forms very small doubly refracting fibers. Most of the lapilli are composed of pale-brown glass, some of it pumiceous, containing microphenocrysts of olivine and labradorite, and altered around the edges to palagonite. Other lapilli are similar except that the glass is black and opaque owing to abundant finely disseminated iron ore. The black glass shows no sign of alteration to palagonite. Among the pyroclastic rocks of Hawaii also, the glassy fragments containing abundant iron ore dust are less readily altered to palagonite than are those in which the iron oxides have remained in solution. Many vesicles in the lapilli are partly filled with zeolite. Angular fragments of coral limestone are present in one specimen of tuff.

The lava is an olivine basalt, containing scattered phenocrysts of olivine up to 2 mm. long. The phenocrysts are partly resorbed and are altered around the edges to iddingsite. The groundmass is intersertal and very fine-grained. It is composed of intermediate labradorite (β = 1.562), colorless monoclinic pyroxene, olivine, iron ore, and colorless interstitial glass. The ore is largely or entirely magnetite. The specimen contains an angular inclusion of dunite, 6 cm. long, composed largely of olivine, but with scattered small grains of magnetite and a few grains of augite.

NUKUFETAU ISLAND

Nukufetau, about 700 feet long and 250 feet wide, lies south of Uvea and east-northeast of Nukuatea. It is composed partly of lava and partly of cinder. The lava is olivine basalt, with scattered phenocrysts of olivine up to 1 mm. long. Most of the phenocrysts show no evidence of resorption, but many are crowded with inclusions of iron ore scattered throughout the crystal, as in olivines in lavas near Auckland, New Zealand (Bartrum, 1942), and in blocks ejected at Kilauea, Hawaii, during the explosions of 1924 (Macdonald, 1944a). A few of the olivine phenocrysts are partly altered to iddingsite. The groundmass is intersertal and very fine-grained, composed of intermediate labradorite (β = 1.562), colorless monoclinic pyroxene, olivine, magnetite, and colorless interstitial glass.

FUGALEI ISLAND

Fugalei, a nearly circular islet about 850 feet across, lies 2 miles east of Uvea. It is built chiefly of lava, with smaller amounts of tuff. Stearns (1945) believes it is probably a lava filling of the crater of an old tuff cone, most of the cone having been cut away by the sea. The lava is olivine basalt, with moderately abundant phenocrysts of olivine up to 1.5 mm. long. The phenocrysts are slightly resorbed and altered around the edges to iddingsite. Some are enclosed in a thin envelope of fresh olivine. The groundmass is intergranular, composed of intermediate labradorite (β = 1.563), colorless pigeonitic pyroxene, olivine, magnetite, and ilmenite.

LUANIVA ISLAND

Luaniva Island, east of Uvea and just north of Fugalei, is about 1100 feet long and 600 feet wide. Like Fugalei, it is composed mostly of lava, with small amounts of tuff. The lava is olivine basalt, containing moderately abundant phenocrysts of olivine up to 1 mm. long. Most of the phenocrysts are euhedral, but some are slightly resorbed. None are otherwise altered. They grade in size into the intersertal groundmass, which consists of intermediate labradorite (β = 1.564), colorless pigeonitic pyroxene, olivine, iron ore, and colorless interstitial glass. The ore is largely magnetite but probably includes some ilmenite. A few irregular flakes of reddish-brown biotite occupy interstices between the grains of other minerals.

PETROLOGIC AFFINITIES

In the islands of the Pacific Ocean two distinct suites of volcanic rocks are clearly recognizable (Marshall, 1912, p. 28; Hobbs, 1944, p. 260). The volcanoes of the central Pacific basin are characterized by the predominance of basaltic rocks, associated with relatively minor amounts of andesine and oligoclase andesite, trachyte, and in a few groups with nepheline basalts and basanites, or their intrusive equivalents. The rock suite of the central Pacific volcanoes is alkaline. Among the examples of this assemblage thus far studied may be mentioned the Society Islands (Williams, 1933; Stark and Howland, 1941), the Marquesas Islands (Chubb, 1930), the Galapagos Islands (Richardson, 1933), the Samoan Islands (Macdonald, 1944a), the Caroline Islands (Yossii, 1937), and the Hawaiian Islands (Macdonald, 1940a; 1940b; 1942).

In contrast, the volcanics associated with the continental rocks on the islands along the border of the Australasian continental platform constitute a calc-alkaline suite. The characteristic rocks are andesite and dacite and smaller amounts of rhyolite, although much basalt also is present. Examples of such island groups are the Tonga, Fiji, New Hebrides, Solomon, Palau, and Marianas archipelagos, with New Zealand at one end and Japan at the other. This belt forms part of the "girdle of fire" which encloses the true Pacific Basin.

The rocks of the Wallis Islands undoubtedly belong to the alkaline suite of the central Pacific volcanoes. They are closely similar to rocks of Samoa and Hawaii. This affinity appears to have been recognized by Marshall (1912, p. 5, 6, 28), for, although he grouped the Wallis Islands as part of the Tonga Archipelago, he never-

theless showed them to lie northeast of the "andesite line" which he considered to mark the edge of the Pacific Basin. Lacroix (1940) considered the Wallis Islands (Uvea) to belong to the circum-Pacific belt, but he appears to have had only a single specimen of basalt from them, and the present study demonstrates beyond question

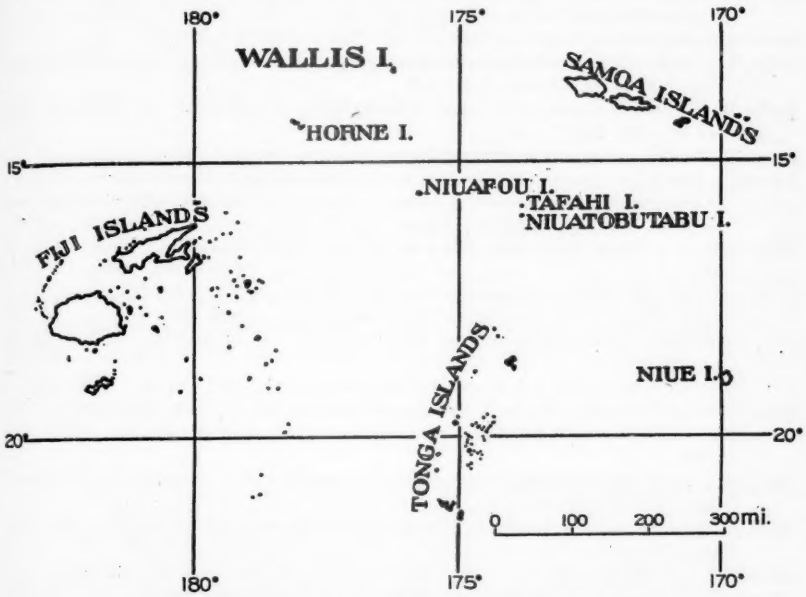

FIGURE 2.—*Map showing position of the Wallis islands*

the similarity of their lavas to those of the central Pacific volcanoes and the dissimilarity to those of the circum-Pacific belt.

The active volcanic island Niuafou, about 160 miles south of Uvea (Fig. 2), also was classed by Lacroix with the circum-Pacific volcanoes. The writer has not studied the rocks of Niuafou, but the physical features of the island (Jaggar, 1931) are such as to indicate that it too probably belongs with the central Pacific volcanoes. The Horne Islands, 140 miles southwest of Uvea (Fig. 2), consist of deeply weathered andesite lavas and breccias, and minor amounts of Miocene limestones, marls, sandstones, and conglomerates (De la Rüe, 1935). They thus clearly belong to the continental margin. The nature of the rocks of Tafahi (Boscawen) and Niuatobutabu islands, 140 miles east-southeast of Niuafou, are unknown. The islands are high and steep, Tafahi rising about 2000 feet above sea level. This, together with their position on the northern extremity of the Tonga Islands ridge, suggests that they are probably andesitic, with continental affinities. The border of the continental platform thus probably passes north of Tafahi Island, south of Niuafou Island, and between the Horne and Wallis Islands.

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VOLCANISM AND PETROGENESIS AS ILLUSTRATED IN THE HAWAIIAN ISLANDS: A DISCUSSION OF THE ORIGIN OF MELILITE-NEPHELINE BASALTS IN THE PACIFIC

BY HAROLD T. STEARNS

ILLUSTRATIONS

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3. Eroded Tertiary volcano on Oahu with Recent nepheline-melilite lava flow..... 874

Daly (1944) has recently advanced new support for his hypothesis that melilite-nepheline basalts, in the Pacific, particularly in the Hawaiian Islands, are due to the absorption of thalassic carbonate deposits by primary basaltic magmas. He assumes that the top of such deposits were about 15,000 feet below sea level and

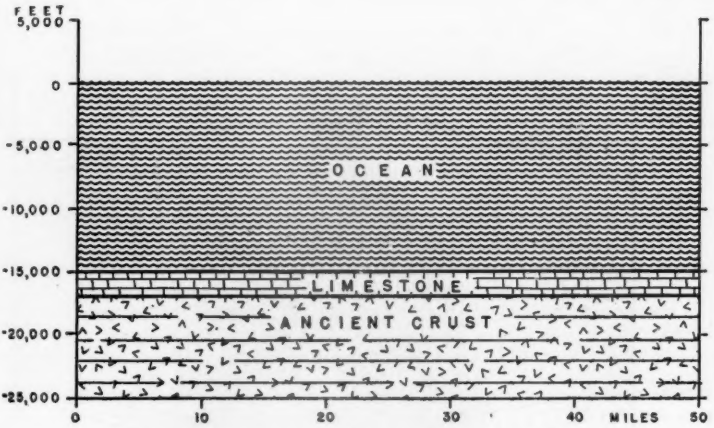

FIGURE 1.—*Pre-Tertiary section of the Pacific at site of Oahu, according to Daly's hypothesis*

that the deposits were perhaps as much as 1200 feet thick prior to the formation of the Tertiary volcanoes (p. 1389). This condition is shown in Figure 1 with the thickness of the limestone exaggerated. He believes that loading of the crust by the Tertiary volcanic piles bowed down the sediments still farther until they "ultimately came into contact with the molten, abyssolithic basalt at levels where much gas was freed from the melt and where two-phase convection was lively" (p. 1389). This condition is shown in Figure 2.

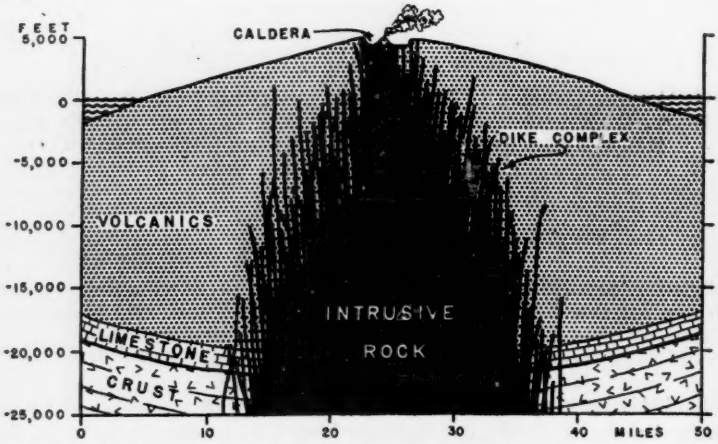

FIGURE 2.—*Tertiary volcano on Oahu at the time of extinction, with the limestone down-bowed according to Daly's hypothesis*

The pre-Tertiary limestone and crust are completely replaced by intrusive rock under the caldera, but, even if absorption of limestone did occur, no alkaline lavas are present in the section above sea level.

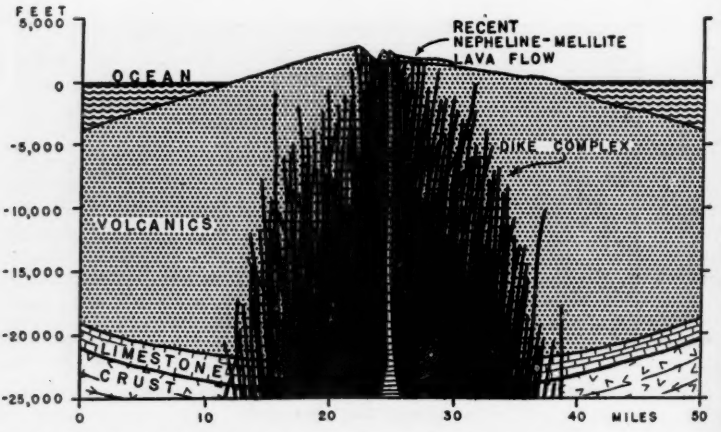

FIGURE 3.—*Eroded Tertiary volcano on Oahu with Recent nepheline-melilite lava flow.*

The flow erupted through the Tertiary dike complex (feeding dike exaggerated) with no opportunity for absorption of limestone. (The horizontal sill-like bodies in Figures 2 and 3 are caused by the stipple pattern running into the dikes when the drawing was reduced.)

Detailed stratigraphic and petrographic work by the U. S. Geological Survey in the Hawaiian Islands controverts the hypothesis. During those studies several thousand lava flows were examined in thin section, and not a single one making up the original volcanic domes contains a crystal of nepheline or melilite, although

nepheline is present in small amount in the norms of some rocks. (*See* Bibliography.) However, many Pleistocene and Recent lava flows, especially in the Honolulu volcanic series of the Koolau Range of Oahu, are rich in nepheline and melilite. All such flows in the Hawaiian Islands rest on deep soils or on valley floors indicating that a long erosion period intervened between them and the Tertiary volcanics. Some of these nepheline-bearing flows—namely, the Maunawili, Ainoni, and Kaneohe volcanics—and the melilite-nepheline Mokulea basalt (*see* geologic map of Oahu) rose through narrow dikes in the very heart of the Tertiary dike complex that built the Koolau Volcano on Oahu. It is difficult to see how such magmas had a chance to contact either the hypothetical thalassic type of limestone or interbedded coral reefs, if such exist (Fig. 3), because these particular alkaline magmas were confined by dense strong Tertiary dikes from abyssal depth to the surface (Stearns and Vaksvik, 1935, p. 197). Nepheline-bearing rocks in other parts of the world may have resulted from the assimilation of limestone, but it is believed that alkaline lavas in Pacific islands have originated in some other way.

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